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The Proceedings of the International Conference on Applied Innovations in IT, Volume 13(5), contains selected papers accepted for publication from those presented at several international scientific events. This issue features contributions from the International Conference for Pure Science and Information Technologies (ICPSIT 2025), organized by the College of Education for Pure Science, Wasit University, Iraq, as well as from the International Scientific Practical Conference on "The Role of Renewable Energy on a Global Scale within the Framework of the 'Green Economy' and the Fourth Industrial Revolution: Innovations, Technologies and Ensuring Sustainable Development," organized by the Tashkent University of Applied Sciences and the Tashkent State Technical University named after Islam Karimov, Uzbekistan. Additional contributions are included from the International Conference on Advances in Engineering and Technology Toward Future Sustainability (ICETFS 2025), held in Manila, Philippines. This volume also includes selected articles prepared specifically for the ICAIIT 2026 Special Issue, covering recent advances and applied research results contributed by international authors.

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ABOUT THIS SPECIAL ISSUE

The Proceedings of the International Conference on Applied Innovations in IT (ICAIIT), Volume 13(5), represents a special issue that consolidates high-quality, peer-reviewed research papers from multiple international scientific events, along with contributions submitted directly by international authors. This volume reflects a multidisciplinary approach, integrating advances in engineering, information technologies, renewable energy, and sustainable development.

All papers included in this issue were selected through a rigorous peer-review process and subsequently organized into a unified thematic framework. The contributions were grouped into the following research areas:

1. Communication Technologies and Hardware
2. Data Transport Technologies
3. Control and Automation
4. Data Analysis and Processing
5. Statistical Modelling and Analysis and their Applications in Life Sciences
6. Information Technology in Economics
7. Power Engineering

By combining research outcomes from several international conferences into a single publication, this special issue provides a comprehensive overview of current scientific trends and fosters interdisciplinary collaboration among researchers and practitioners worldwide.

About International Conference for Pure Sciences and Information Technology (ICPSIT 2025)

The International Conference for Pure Sciences and Information Technology (ICPSIT 2025) was held on October 29–30, 2025, at the College of Education for Pure Science, Wasit University, Iraq. The conference was organized to bridge the gap between fundamental scientific research and modern technological applications.

ICPSIT 2025 brought together researchers, academicians, and industry professionals to exchange knowledge and present recent advancements in pure sciences and information technologies. The conference covered key areas including mathematics, information theory, computer science, physics, communication technologies, and information technology in economics.

The event featured keynote lectures, technical sessions, and workshops focusing on emerging topics such as artificial intelligence, cybersecurity, Internet of Things (IoT), data analytics, and computational modeling. By integrating theoretical and applied research, ICPSIT 2025 contributed to the development of innovative solutions and strengthened international scientific collaboration.

Selected high-quality papers from the conference were included in this special issue of ICAIIT, highlighting interdisciplinary research and practical applications in science and technology.

About International Scientific and Practical Conference on Renewable Energy and Green Economy (Tashkent, 2025)

The International Scientific and Practical Conference on "The Role of Renewable Energy on a Global Scale within the Framework of the Green Economy and the Fourth Industrial Revolution: Innovations, Technologies and Ensuring Sustainable Development" was held on October 3–4, 2025, in Tashkent, Uzbekistan.

The conference was organized by the Ministry of Higher Education, Science and Innovation of the Republic of Uzbekistan, the Ministry of Energy of the Republic of Uzbekistan, and the Tashkent State Technical University named after Islam Karimov. It served as a platform for discussing global challenges related to renewable energy, environmental sustainability, and digital transformation.

The conference brought together researchers, educators, doctoral students, and industry specialists to share scientific findings and practical solutions. Key topics included renewable energy systems, the transition to a green economy, climate change mitigation, integration of artificial intelligence in environmental protection, and technological challenges in modern energy systems.

The event emphasized the importance of reducing carbon emissions, improving energy efficiency, and ensuring environmental security through innovative technologies. Selected papers from this conference were incorporated into the ICAIIT special issue, contributing to the advancement of sustainable energy research.

About International Conference on Advances in Engineering and Technology Toward Sustainable Development (AETSD 2025)

The International Conference on Advances in Engineering and Technology Toward Sustainable Development (AETSD 2025) was held on November 27–29, 2025, at De La Salle University, Manila, Philippines.

AETSD 2025 aimed to address contemporary challenges in engineering and technology within the framework of sustainable development. The conference brought together leading researchers, industry experts, and policymakers to exchange knowledge and present innovative solutions aligned with the United Nations Sustainable Development Goals (SDGs).

The conference program included keynote presentations, technical sessions, and research discussions covering a wide range of topics such as renewable energy, sustainable infrastructure, environmental engineering, smart systems, and digital transformation. Distinguished speakers from international institutions contributed insights into cutting-edge technological developments.

All submitted papers underwent a double-blind peer-review process, ensuring high academic quality. Accepted papers were presented both physically and virtually, enabling broad international participation. Selected contributions were included in this ICAIIT special issue, reflecting global perspectives on sustainable engineering and technological innovation.

About Integration of Contributions

The integration of papers from these conferences into a single special issue allowed for the consolidation of diverse research directions into a coherent scientific framework. Despite the variety of topics and geographical representation, all contributions were aligned with common themes of technological innovation, sustainability, and applied research.

This unified approach enhances the scientific value of the volume and provides readers with a comprehensive understanding of current developments across multiple disciplines, supporting future research and international cooperation.

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SECTION 1

COMMUNICATION AND DATA TRANSPORT TECHNOLOGIES

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Modeling of Traffic Engineering Queues with QoS Differentiation

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Abstract: The paper analyzes the Class-Based Traffic Engineering Queue (CB-TEQ) model, which provides organization and management of class queues on the router interface, supporting differentiated and balanced packet service. It is demonstrated that the advantage of CB-TEQ lies in the implementation of an optimal interface bandwidth allocation between class queues based on a linear programming problem. At the same time, a shortcoming of the model has been identified, related to the need for heuristic selection of the normalization coefficient. To address this issue, an Enhanced Class-Based Traffic Engineering Queue (ECB-TEQ) model is proposed, in which the normalization coefficient is considered as a control variable. This enabled the calculation of the optimal value of the normalization coefficient by solving a nonlinear optimization problem with a modified criterion and a system of constraints. The results of experimental studies confirmed the efficiency of ECB-TEQ, in particular its ability to provide the maximum level of differentiation when servicing packets in different class queues.

1 INTRODUCTION

Quality of service (QoS) is a primary concern in modern communication networks [1], [2]. Complexity of QoS provision is due to several factors, including geographical distribution, environmental heterogeneity, network state dynamics, growth in the number of users and services, limited resources, and the need to support various QoS models [3]-[5]. Ensuring QoS requires the coordinated operation of all OSI layers protocols, particularly at the network layer, where scheduling and resource allocation mechanisms play a crucial role [4]-[7]. They determine the bandwidth allocation between packet queues on the network equipment (routers and switches) and form the basis of the IntServ and DiffServ models [8], [9]. These mechanisms must support multiple queues, provide service guarantees, ensure consistent packet processing, and be easy to implement. In practice, routers use several mechanisms simultaneously, and their effectiveness is determined by the mathematical models and methods used.

Modern queue management mechanisms are in demand in various network environments, as confirmed by studies [10]-[18]. The tasks of optimal resource allocation and QoS assurance are relevant in general-purpose networks [10], [19]-[21], industrial IoT solutions [11], specific environments [12], [13], [15], [17], and hierarchical solutions [16], [19], [20]. This highlights the importance of adaptive queue management methods for a wide range of scenarios. The purpose of this work is to optimize the queue management process to ensure differentiated packet servicing at the router interface. To this end, the existing solution will be considered, and its enhancement will be proposed, followed by proving its effectiveness on a set of computational examples.

2 BASIC CLASS-BASED TRAFFIC ENGINEERING QUEUE MODEL

Let the Class-Based Traffic Engineering Queue (CB-TEQ) model, introduced in [21], serve as the basis for further enhancement. Within the CB-TEQ model, the resource allocation problem is considered. Pre-aggregated packet flows are directed into class queues based on the proximity of their class values [21]. The following notations are used:

- B – router interface bandwidth (bits per second);
- N – number of class queues on the interface;
- b_i – interface bandwidth allocated for the ith class queue;
- r_i – average intensity of the aggregated packet flow arriving at the ith queue (bits per second), $i = \overline{1,N}$.

The variables b_i are subject to constraint:

$$b_i \geq 0, \quad (1)$$

$$\sum_{i=1}^{N} b_i = B. \quad (2)$$

Additionally, nonlinear overload prevention conditions must be met related to the optimal resource allocation and balanced bandwidth utilization among queues under the Traffic Engineering Queues [21]:

$$h_i^{\alpha} r_i \leq \alpha b_i \ \ (i = \overline{1,N}), \quad (3)$$

where α is the control variable for the upper dynamically regulated bound on queue utilization, following the condition:

$$0 < \alpha \leq 1. \quad (4)$$

The h_i^{α} is the class coefficient for balanced interface bandwidth allocation for the ith queue:

$$h_i^{\alpha} = 1 + i/(N \cdot D) \ \ (i = \overline{1,N}). \quad (5)$$

In addition, D is the normalization coefficient that determines both the influence of the queue class on h_i^{α} and the degree of bandwidth balancing across queues. As shown in [19], [20], the minimum allowable value D_{min} ensures the highest level of service differentiation among packets in different class queues. A higher queue class corresponds to a larger h_i^{α}, which in turn leads to lower utilization ρ_i for the same boundary value α. Within the framework of model (1)-(5), the utilization coefficient is given by:

$$\rho_i = \frac{r_i}{b_i} \ \ (i = \overline{1,N}). \quad (6)$$

An increase in the normalization coefficient D reduces the influence of the queue class on allocated bandwidth. Using expressions (3)-(6), the model provides differentiated allocation of router interface bandwidth among class queues. Maximum differentiation is achieved when D is set to its minimum permissible value [19], [20]. Condition (3) is nonlinear because of the product of the control variables b_i and α, and bandwidth balancing is ensured by α. As shown in [21], (3) can be transformed into a linear form:

$$\beta h_i^{\alpha} r_i \leq b_i \ \ (i = \overline{1,N}), \quad (7)$$

where β is the control variable, inversely proportional to the upper bound of queue utilization α, i.e.,

$$\beta = \frac{1}{\alpha}. \quad (8)$$

The variable β is subject to the constraints:

$$\beta > 1. \quad (9)$$

The queue management optimality criterion is given by:

$$\beta \rightarrow max. \quad (10)$$

Criterion (10) minimizes the upper bound of queue utilization, with weights determined by the class values in (3) and (5). Thus, the CB-TEQ solution (1)-(10) is a linear programming problem with criterion (10) and constraints (1), (2), (7), and (9).

3 ENHANCED CLASS-BASED TRAFFIC ENGINEERING QUEUE MODEL

A limitation of the CB-TEQ model is that it requires prior configuration, namely the heuristic selection of the normalization coefficient D. This coefficient must be set so that, first, the minimization problem (10), subject to constraints (1), (2), (7), and (9), admits a solution, and second, that a sufficient degree of differentiation is achieved in the service of packets across different queues. To address this, the present work proposes an enhancement of the CB-TEQ model in which the optimal (minimum) value of D (5) is computed jointly with the control variables β and b_i. This approach guarantees differentiation in packet servicing across queues. Then, considering (5), condition (7) is reformulated as follows:

$$\beta r_i (1 + i/(N \cdot D)) \leq b_i \ \ \left(i = \overline{1,N}\right). \quad (11)$$

Analysis of expression (11) and the results obtained in works [19]-[21] show that, with an increase in the coefficient D, there will be no differentiation in the servicing of packets across different queues, since their utilization coefficients (6) will be equal. To increase service differentiation, the normalization coefficient must be reduced to a specific, but previously unknown, value. Thus, with a very small D, it will be impossible to satisfy the requirements of condition (11) even with a small load on the queue. Therefore, there is a need for an optimization formulation of the problem to determine the minimum acceptable value of the normalization coefficient D.

Table 1: Input data variants.

Var. #	Class queue load, r_i								R	B	D_{min}	ρ_{min}	ρ_{max}
	1	2	3	4	5	6	7	8					
1	14	9	9	5	11	8	21	13	90	100	5.413	0.8441	0.9774
2	9	14	9	13	21	8	11	5	90	100	4.825	0.8283	0.9747
3	5	11	8	21	13	9	14	9	90	100	5.3	0.8413	0.9770
4	5	11	8	25	15	12	14	0	90	100	4.95	0.8498	0.9754
5	5	11	8	25	15	12	14	×	90	100	5.657	0.8498	0.9754
6	5	20	8	30	15	12	0	0	90	100	4.2	0.8485	0.9711
7	5	20	8	30	15	12	0	×	90	100	4.8	0.8485	0.9711
8	5	20	8	30	15	12	×	×	90	100	5.6	0.8485	0.9711
9	5	20	10	30	25	0	0	0	90	100	4	0.8649	0.9697
10	5	20	10	30	25	0	0	×	90	100	4.57	0.8649	0.9697
11	5	20	10	30	25	0	×	×	90	100	5.33	0.8649	0.9697
12	5	20	10	30	25	×	×	×	90	100	6.4	0.8649	0.9697
13	12	7	8	5	10	8	19	11	80	100	2.43	0.7086	0.9511
14	5	17	8	26	24	×	×	×	80	100	1.794	0.7416	0.9349
15	10	6	8	5	9	8	15	9	70	100	1.4	0.5833	0.9180
16	5	14	8	21	22	×	×	×	70	100	1.673	0.6259	0.8932
17	14	11	9	6	13	8	21	13	95	100	11.275	0.9185	0.9890
18	7	21	10	32	25	×	×	×	95	100	13.28	0.93	0.9852

In (11), the set of control variables now includes not only β and b_i, but also D. Consequently, expression (11) becomes nonlinear with respect to the specified control variables. The next constraint is imposed on the new control variable:

$$D > 0. \quad (12)$$

With the expansion of the control variable set, the optimality criterion must also be revised. In this work, the following criterion is proposed:

$$(\beta - kD) \to max, \quad (13)$$

where k is a sufficiently large positive constant introduced to prioritize the selection of the optimal (minimum) value of D. Thus, the Enhanced Class-Based Traffic Engineering Queue (ECB-TEQ) model is formulated as a nonlinear optimization problem with criterion (13) and constraints (1), (2), (9), (11), and (12).

4 NUMERICAL RESEARCH

Several examples of the queue management problem were examined using different input data variants (Table 1) to identify the factors influencing the optimal values of the normalization coefficient D.

The interface bandwidth B was fixed at 100 Mbps. For clarity, the number of class queues on the interface varied between five and eight. The load on individual class queues (r_i) was selected randomly, but the total load on the interface $R = \sum_{i=1}^{N} r_i$ ranged from 70 to 95 Mbps. Table 1 shows the results of the study for 18 input data variants, for each of which D_{min} was determined using the ECB-TEQ model, and the minimum and maximum values of utilization coefficients (6) for class queues were calculated. For variants in which fewer than the maximum allowable number (eight) of queues were organized, a mark × was placed in the corresponding columns of Table 1. If a queue was created but not loaded, i.e., remained empty, then zero is present in the corresponding column.

Analysis of Table 1 shows that the value of D_{min} is most sensitive to the interface utilization. For example, when the total interface load R was 95 Mbps, D_{min} exceeded 10 (input data variants 17 and 18), whereas with a load of 70 Mbps, D_{min} did not exceed 2 (input data variants 15 and 16). Figures 1 and 2 illustrate the dynamics of utilization coefficients across class queues for input data variants 18 and 15, respectively. As shown in Figure 1, as the coefficient D increases, the utilization coefficients of all queues converge, thereby reducing the level of differentiation in packet servicing across queues and effectively negating the purpose of organizing multiple class queues on the interface.

In addition, the number of formally organized versus actually utilized class queues also influenced the value of D_{min}, although to a much lesser extent. To illustrate this, variants 9-12 in Table 1 are examined in detail.

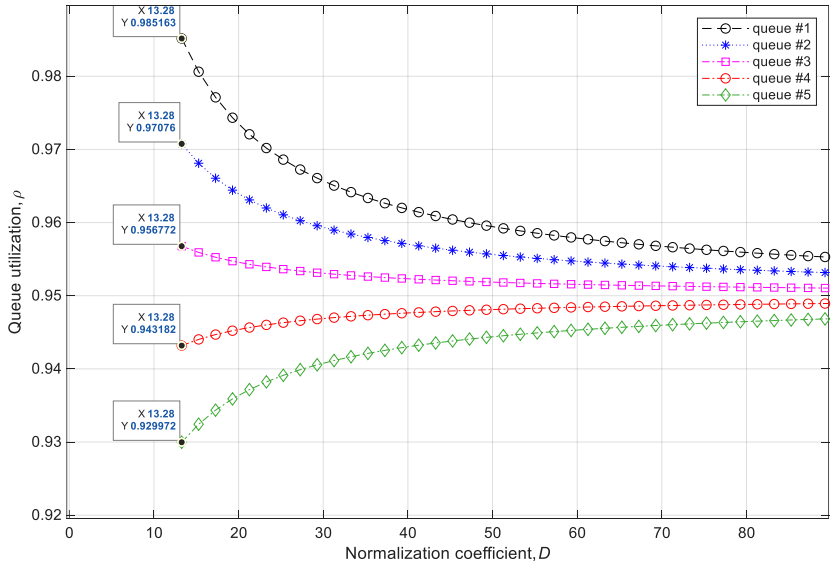


Figure 1: Variation of utilization coefficients across class queues for input data variant 18.

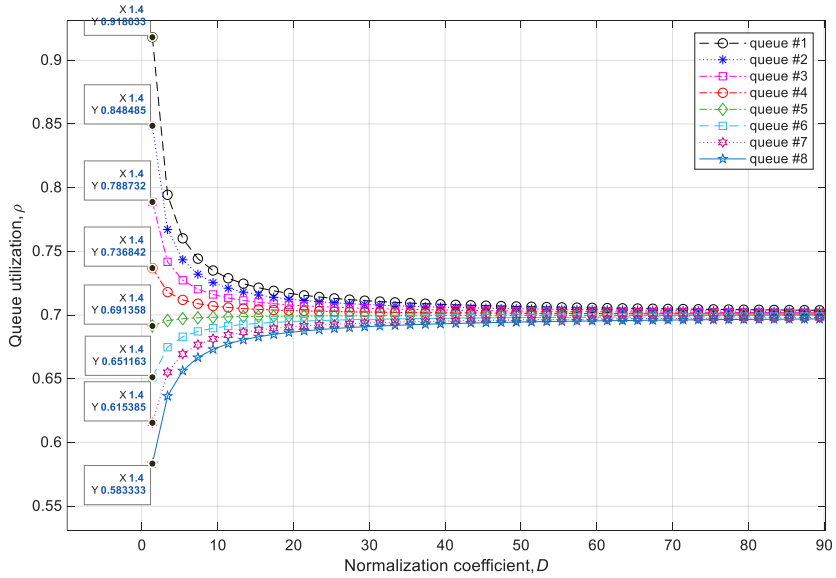


Figure 2: Variation of utilization coefficients across class queues for input data variant 15.

These options share the same traffic structure at the interface, with only queues 1 through 5 being loaded. In variant 12, five class queues were created, whereas in variant 9, eight queues were created; however, queues 6 through 8 remained empty, meaning no packets were assigned to them. From a practical perspective, the ECB-TEQ model produced the same interface bandwidth allocation among the active queues from first to fifth in each case. This resulted in identical values of ρ_{min} and ρ_{max}, but different values of D_{min}, since expression (6) explicitly accounts for the total number of queues organized on the interface (N).

Accordingly, in Table 1, when the number of queues varied from five to eight (variants 9-12), the value of D_{min} changed, while ρ_{min} and ρ_{max} remained constant. A similar situation is observed, for example, in input data variants 4–5 and 6–8. In variants 6–8, between six and eight queues were organized on the interface, but only six were actually utilized (Table 1).

Another factor affecting the determination of D_{min} was the structure of the traffic arriving at the

interface. Even with the same number of organized and active queues and the same total interface load R, differences in flow intensity across individual class queues (variants 1-3) led to variations in D_{min}, although these variations were not substantial.

Therefore, within the CB-TEQ model, the heuristic determination of the minimum value of the normalization coefficient D in expression (6) is a nontrivial task. Its solution is influenced by numerous factors, including the interface utilization, the number of organized and active class queues, and the traffic structure both at the interface in general and within individual queues. Based on experimental results, specific recommendations for selecting the minimum value of D can be formulated, as demonstrated in [19], [20]. However, even minor errors in this process may result in significant changes in queue utilization coefficients (Fig. 1 and 2) and the loss of packet service differentiation.

For this reason, the ECB-TEQ model provides a more robust solution. The study conducted using the input data presented in Table 1 confirmed its effectiveness. The ECB-TEQ model consistently computed the optimal (minimum) values of D (Table 1), ensuring the highest level of packet service differentiation across class queues (Fig. 1 and 2). The trade-off for this extended functionality is the transition from solving a linear programming problem (as in CB-TEQ) to a nonlinear programming problem (ECB-TEQ).

5 CONCLUSIONS

This study examines the well-known Class-Based Traffic Engineering Queue (CB-TEQ) model (1–10), which enables the organization and management of class queues on a router interface while supporting differentiated and balanced packet servicing. In the CB-TEQ framework, the queue utilization coefficient, and consequently delay and packet loss, are directly determined by the queue class. The higher the class of a queue, the lower its utilization coefficient and the higher the level of QoS provided to the packets assigned to it.

A key advantage of the CB-TEQ model is that the optimal allocation of interface bandwidth across class queues is achieved by solving a linear programming problem, which has a favorable impact on the computational complexity of its technological implementation. However, a certain disadvantage is the requirement for heuristic tuning of the normalization coefficient D. If D is set too high, packet service differentiation among queues is diminished. If it is set too low, the optimization problem with criterion (10) and constraints (1), (2), (7), and (9) may have no feasible solution. As the study showed (Table 1), selecting an appropriate value for D is complicated by its sensitivity to the interface state, including utilization level, the number of organized and active class queues, and the structure of incoming traffic.

Therefore, this work proposes an improvement of the CB-TEQ model by including the normalization coefficient D in the set of control variables in addition to β and b_i $(i = \overline{1, N})$. This modification required a revised optimality criterion (13) and an updated set of constraints, namely (1), (2), (9), (11), and (12). The computation of the optimal (minimum) value of the normalization coefficient within the ECB-TEQ model became possible by solving a nonlinear optimization problem, since constraint (11) is nonlinear with respect to the extended set of control variables. The study results presented in Table 1 confirmed both the feasibility of the proposed ECB-TEQ model and its effectiveness in automatically selecting the maximum level of differentiation in packet servicing across class queues.

Future research directions connected with the use of AI techniques to improve scalability and further reduce the computation time required to solve the ECB-TEQ problem. Extending the model to hierarchical queue management is also demanded. In addition, the proposed approach will be prepared for integration into programmable networking environments and adapted for deployment on corresponding network devices.

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An Improved AI-Driven Algorithm of Data Flow Optimization on the Normalized Bipolar Planar Free-Oriented Network Graph

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Abstract: In this work, an improved algorithm has been developed for data flow optimization on the normalized bipolar planar network graph (NBPG) with free-oriented edges, that is taken as an enhanced model of a software defined network with flexibly reconfigured channels. The NBPG-model differs from known analogues by a special normalization of an arbitrary V-vertex graph structure as successive transforms of a primitive 3-vertex graph. Hereby, the searching for optimal paths in Maxflow problem yields a combinatorial task of constructing the full set of potentially optimal paths (POPs), for which a recursive heuristically solution can be found. Due to the NBPG-model generality, a complete set of potentially optimal paths on the uniform NBPG graph with V_{max} vertices can be applied for any given NBGP(V) graph with $V \le V_{max}$. The combinatorial task of POP searching on the normalized NBPG graph has quadratic complexity, and designing a program code for its computation is not a trivial case. To overcome this issue, AI have been involved for the explicit recursive constructing the full set of POPs on arbitrary normalized NBGP(V) graph via a public GPT-model training by the clustered combinatorial sequences. So, the optimal data flow distribution by criterion of maximum throughput on individual graphs is reduced to a simple cycle of processing a compact universal pre-defined set of potentially optimal paths that is similar for all the normalized graphs with parametrically limited vertex quantity. These features allow to simplify and speed up dynamic resource allocation in modern telecommunication networks with reconfigurable channels, expand their functionality and increase the quality of service when bidirectional multiproduct data transfer.

1 INTRODUCTION

One way to increase the telecommunication network's resilience to negative factors is optimization the data flows for the best use of available resources in changing situations (failure of its elements, external interference, etc.). An important criterion for the use of available resources is the total data flow of the network, and the task of increasing it, is also known as the “MaxFlow problem” (MFP) [1], [2].

Historically, the MFP problem arose in logistics networks for delivery of some homogeneous product (gas, oil, etc.) from the producer location (source S) to the accumulation terminal (T), where no intermediate flow sources and accumulators exist in the logistics network, as well as product flow channels do not intersect [3].

A typical math model of a logistic network is directed weighted planar graph (DWPG) with two special vertices – the product source S and the end terminal for product delivery T (aka graph-poles). The mono-directed arcs of the graph define the product-channel capacities. The visual form of DWPG is a plane network without any arc intersections [4].

Logistical approach to MFP-problem is based on the Ford-Fulkerson theorem: the maximal network flow F identically equals the minimal cut between poles S and T of the network graph. The algorithm to find F: take a chain (ST-path) crossing any cut only once, impose as large a chain-flow f, delete saturated chain-arks. Repeat these steps until S and T have no connections. Eventually, F is the sum of all the chain-flows {f} [5].

The Ford-Fulkerson algorithm (FFA) in [5] contains an inaccuracy: when computing partial flow f, it is wrong to take an arbitrary ST-path. Instead, only the shortest path in hop-metrics must be selected each time. In fact, the Edmonds-Karp algorithm (EKA) of $O(V \cdot E^2)$ complexity is considered a de facto FFA implementation, where the shortest path on the graph is selected at each iteration using the breadth-first search (BFS) [6], [7]. It is preferable for sparse graphs with minimal number of edges.

Based on FFA, alternative approaches to MFP problem have been developed. One of the most common is Dinitz blocking flow algorithm (DBA) with $O(V^2 \cdot E)$ complexity, that is similar to EKA, but can run faster on dense graphs with maximal number of edges [8]. For ST graphs with binary arc-weights the Goldberg-Taryan push-relabelling algorithm (GTA) of $O[\min(V^{2/3}, E^{1/2})]$ complexity may be more effective. It is based on Dinitz DBA method, and simulates the water flow distribution in a pipeline network assuming the "excess pre-flow" at the input of the graph vertices except the source node [9], [10].

For special cases of the ST-graph structure, the alternative Goldberg-Rao algorithm (GRA) with $O(V \cdot E)$ complexity can exceed the GTA speed [11]. In 2006, D. Papp presented an improved Goldberg-Rao algorithm (PGRA) for MFP problem that works not only for graphs with unitary arc capacities, but also for integer or non-negative real values [12]. An algorithm for Maxflow estimation (MFE) on the undirected weighted ST-graph was proposed by P. Christiano et al, that uses Laplace matrix to solve a system of linear equations for electric flow. The authors claim the algorithm is the fastest among those known at that time [13].

The MFP logistical approaches based on FFA-method are also widely used for data-flows optimization in telecom networks, yet, they do not fully consider potentials of modern digital channels with flexibly reconfigurable capacities, and therefore, are less effective [14], [15].

A combinatorial method for MFP-like problems solution was presented by M. Rajouh on the base of Pontryagin maximum principle with a set of necessary extremum-conditions that must be satisfied at each iteration. This allows to pre-screen out unacceptable combinatorial options for finding the optimal solution to the problem, and thereby reduce the number of required iterations and speed up the algorithm by selecting a compact set of promising candidates at each step of the algorithm [16]. The theoretical foundations of MFP problem solving on different types of network graph models are presented in [17].

A comprehensive review of methods and algorithms for computing the maximum flow on a directed weighted ST-graph is given by D. Williamson, that extends the scope of network flow research to multi-product problems and provides a detailed analysis of 2-product case. Also, the concept of ST-flow in an undirected graph is clearly defined, where any edge has an arbitrary positive orientation and consists of two oppositely directed arcs of equal capacity [18].

An extended approach to MFP study is presented in [19]. Unlike logistical bipolar DWPG graph model, the network performance (Maxflow) is defined on an 3-pole free-oriented graph (FOG). Related algorithm for a 6-vertex graph is presented in [20].

The telecom networks have some common properties with electrical circuits. An electricity flows optimization method (EMFP) is exhibited in [21] that seeks to achieve the most equal flow on all edges in a subset of the edges of a graph. The task is also extended to the Almost Equal Maximum Flow Problem (AEMFP), where the values of the electricity flow in individual network links differ from the average “almost equal maximum flow” according to a certain deviation function.

A near-optimal routing algorithm for SDN networks is proposed in [22] based on the MaxFlow/MinCut theorem. It is shown that distributing flow along minimum transit routes improves network performance compared to traditional shortest path algorithms. To optimize the multimodal flows in logistics systems, genetic algorithm can be applied, which is commonly used in vehicle routing problems (VRP). It imitates Darwin's natural evolution in a transport network model and includes five processing steps: task encoding, population initialization, determination of selective operations, mutation, selection process [23].

A survey on algorithms of MaxFlow/MinCost problems is given in [24] where deterministic tasks on directed weighted ST-graphs considered with exactly known inputs, constraints and objectives, with an emphasis on the worst case in terms of the duration of the problem solution time. The work focuses algorithms faster then known before. Noted, that GRA-algorithm is weakly polynomial, while existence of a strongly polynomial $O(V \cdot E)$ algorithm was shown by [25] and by [26]. Also, interior point methods (IPM) for MFP solutions discussed.

In this work, combinatorial task of data flow optimisation in telecom networks is considered with particular emphasis on the modern digital channels that provide flexibly reconfigurable capacity.

2 MOTIVATION AND OBJECTIVES OF THE WORK

The current state analysis of the maximum flow problem (MFP) shows that methods and algorithms for optimizing flows in telecommunication networks mainly explore the legacy logistical approach to product delivery systems with the use of directed weighted planar graph (DWPG) as a network model, that has two particular vertices (poles): S - the manufacturer product source; T - the final terminal for accumulating and further distribution the product.

The main goal herewith is estimation of the potentially feasible network flow F. Despite the diversity of known methods and approaches to solving the MFP problem, one of the most popular today MFP solutions for telecoms is Dinitz blocking flow algorithm (DBA) with $O(V^2 \cdot E)$ complexity, that could be taken as a relevant pattern for comparison.

The core drawbacks of the popular today approaches to the Maxflow problem solution in the context of telecoms applications are the following.

- The Maxflow value F itself as MFP solution result indicates network potential capacity, but it remains unknown "how" to schedule the flows around the network paths;
- the directed weighted planar graph DWPG with unidirectional channels is inadequate model for telecom networks transmitting data in opposite directions;
- the DWPG-graph with fixed arc-capacities is not a relevant model to modern digital channels with flexibly reconfigurable capacities, and therefore, is less effective;
- searching-based MFP algorithms on DWPG graph model principally limit computational performance compare to combinatorial approach, that may be critical in special software defined ad hoc networks.

Consider above, an extended Maxflow problem (MFP+) arise: Find the network maximal flow F, along with its optimal distribution over ST-paths $\{P_i\}$ and network minimal cut structure $\{C_E\}$.

According to this, *the work aims MFP$^+$ problem solution in order to increase the overall network performance and resilience*.

To achieve this, the following objectives are set:

- normalization of ST-planar network graph;
- combinatorial construction of the shortest path-searching tree (SPST);
- development an AI-driven algorithm of data flow optimization and scheduling.

3 NORMALIZATION OF THE FREE-ORIENTED ST-PLANAR NETWORK GRAPH

The AI-driven algorithm of data flow optimization for the extended MFP+ problem declared above is based on an enhanced bipolar model of a modern software-defined network with flexibly reconfigurable edge-capacities, i.e., a specially normalized free-oriented ST-planar graph G(V) with V≥3 vertices, that is defined as followed:

- graph G(V) has a full set of edges that are possible for a planar graph with V vertices; if actual network has a smaller number of links, then a correspondent missed edge in G(V) is marked by zero-capacity;
- any graph G(V>3) is constructed successively by adding a new vertex V and three new edges to the G(V-1) graph, starting from the primitive graph V(3); the first of any three new edges has "vertical" view, second – the "left", third – the "right";
- vertices "1" and "2" always mean two open poles in any graph G(V), and there is no matter what pole is the source S or terminal T, because graph G(V) is invariant to data-flows directions.

Figure 1 for G(5) graph illustrates the intuitively clear way how to transform the initial 3-vertex primitive graph G(3) into arbitrary V-vertex normalized ST-planar graph by successive adding new vertices. The graph edges are indexed by 1÷9, and their (unitary) capacities shown in parentheses. It is clear that normalized graph G(V) has 3·(V-2) edges. The graph G(V) openness means that more complex network frameworks can be hierarchically constructed through integration diverse G(V) graphs.

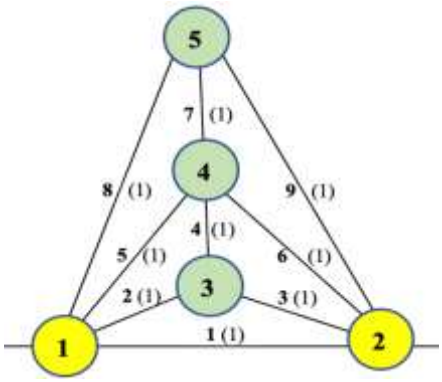


Figure 1. Normalized free-oriented ST-planar graph G(5).

4 COMBINATORIAL DESIGN OF THE SHORTEST PATH-SEARCHING TREE

The normalized bipolar planar graph G(V) introduced above as an enhanced SDN-model allows to solve the extended Maxflow problem (MFP+) even for less computation time compare to the popular algorithms for classic MFP due to combinatorial construction and fast processing of the shortest paths searching tree (SPST), that is a bottleneck in MFP/MFP+ tasks resolution.

For instance, the Dinitz algorithm (DBA) with $O(V^2 \cdot E)$ complexity, if applied to the normalized planar graph G(6), yields the run-time $V^2 \cdot E = V^2[3(V-2)] = 3 \cdot V^3 - 6 \cdot V^2 = 3 \cdot 6^3 - 6 \cdot 6^2 = 432$. Next will be shown, if SPST-software applied, the run-time is reduced to $[(V-2)^2+1] = [(6-2)^2+1] = 17$ (i.e., 25.4 times faster). This gap in computation speed grows rapidly with increase of the network scale, i.e. with large numbers V of graph G(V) vertices. The SPST-hardware application with the use of FPGA LSI may drop down the run-time to several clock generator strobes.

Such performance speed up is achieved due to generic combinatorial properties of the normalized graph G(V) and the regular structure of its shortest paths tree SPST, that are logically transparent, predictable, universal, and therefore, could be designed and saved in advance on processor memory to eliminate a lot of routine operations in real time mode. In fact, the SPST of a normalized graph G(V≥3) can be effectively used for any graph G'(V') with a smaller number of vertices $3 \le V' \le V$.

Consider in detail construction of SPST on a normalized bipolar planar graph G(V) for given number of vertices V.

Note the following aspects.

- SPST must be a full set of potential candidates on ST-path-searching for flow-conductivity;
- SPST-paths must be (partially) ordered by length increase in hop-metrics (according to "shortest path-maximal flow at each step" in popular MFP-algorithms EKA, DBA etc.);
- the number of really possible paths is less then SPST power, as not all the SPST-options are mutually independent.

Let see the SPST design for the graph G(5) in Fig.1. The sub-graph G(3) has two ST-paths (in edge IDs): (1), (2, 3). Vertex "4" adds 3 options more: (5, 6), (5, 4, 3), (2, 4, 6), where the last two ones are excusive alternatives (i.e., only one of them might be possible).

The latter fact can be proven by reversal. Suppose, unitary flows exist for two 3-hop paths: f1(5, 4, 3) and f2(2, 4, 6). Then the following edge-capacities must be: 2(1), 3(1), 4(2), 5(1), 6(1). Note, that path-searching always tries to check the shortest-path options at each step. So, edges 2, 3, 5, 6 will be chosen for flows and saturated (set to zero) earlier then paths (5, 4, 3) and (2, 4, 6) will be examined. Therefore, no more 3-hop flows f1(5, 4, 3) or f2(2, 4, 6) are possible.

When look at the graph G(5) in Fig. 1 it is clear, that five additional options of path searching appear: (8, 9), (8, 7, 6), (5, 7, 9), (8, 7, 4, 3) and (2, 4, 7, 9). So, the following features of SPST can be fixed:

- The "vertical" graph-edges 4, 7, 10, 13, etc. may get flow only in one of two exclusive directions (up XOR down);
- each new graph vertex adds a "vertical" edge and two more potential paths;
- each new "vertical" edge triggers $(2 \cdot V - 5)$ more path-searching options of the SPST set.

Based on of a normalized planar graph G(V) properties, it is easy to recursively construct the shortest path searching tree SPST for arbitrary graph G(V) with the use of additive tuples $\Delta P(V \ge 3)$:

$$\begin{cases} P(V) = \{P(V-1), \Delta P(V)\}; \\ P(3) = \{(1), (2, 3)\}; \\ SPST(V) = \{P(3), \Delta P(4), \Delta P(5), ..., \Delta P(V)\}. \end{cases}$$

The SPST power estimation for V≥3 is:

V = 3 4 5 6 7 8 ...

$||SPST|| = (V-2)^2+1 = 2, 5, 10, 17, 26, 37$ and so on.

For a large number of graph vertices V, the manual building of tuples ΔP(V) becomes a tedious routine deal, while the programming of a relevant computerized algorithm is not a trivial task, that might be set as a next step of MFP+ research.

Consider the fact, that shortest path-searching tree can be fixed in advance as a single $SPST(V_{max})$ set valid for all the normalized graphs G(V) with limited number of vertices $V < V_{max}$. Besides, the SPST framework is shaped by regular forms of digital figures with intuitively clear logic and predictable structure. Due to this, an issue arises: how to make AI solve the routine work of SPST building instead of doing it manually or writing a code for computer?

A modern AI model is pretrained on huge amount of data that allows it to quickly match a new, atypical client given task with patterns or structures known before, even if they are hidden. But AI has no real "human mind", and therefore, the best strategy of AI utilization is a dialogue form of AI-Client

interaction, aka “Human in the Loop”. An important question is what kind of AI-Client interface can be applied herewith [27], [28].

5 AI-DRIVEN GENERATION OF THE SHORTEST PATH-SEARCHING TREE

The results of the previous section 4 indicate that the common idea of recursive design of the shortest path tree SPST(V) on the free-oriented normalized planar graph G(V) is intuitively clear, and theoretically allows AI-driven generator for any finite V≥3.

The linear growing power of recursively added tuples ΔP(V) with O(2·V−5) complexity makes it possible to manually compose a comprehensive AI-teaching sequence divided in training section (V≤5) and testing section (V= 6, 7). The set of AI-training tuples ΔPV) for V≤5 is shown in Table 1.

Table 1: The AI-training Shortest Path-Searching tuples.

V	3	4	5
Initial paths quantity	1	2	5
Tuples quantity	1	3	5
Tuples ΔP(V)	ΔP(3)	ΔP(4)	ΔP(5)
2-hop paths	(2, 3)	(5, 6)	(8, 9)
3-hop paths	–	(5, 4, 3) (2, 4, 6)	(8, 7, 6) (5, 7, 9)
4-hop paths	–	–	(8, 7, 4, 3) (2, 4, 7, 9)
Total paths quantity	2	5	10

A brief protocol of human Client-AI interaction is presented below for Google Gemini GPT.

Client: Given a training sequence with tuples ΔP:
V = 3; ΔP= (2, 3).
V = 4; ΔP= (5, 6), (5, 4, 3), (2, 4, 6).
V = 5; ΔP= (8, 9), (8, 7, 6), (5, 7, 9), (8, 7, 4, 3), (2, 4, 7, 9).
Find a solution for V= 6: ΔP = ?

AI: Thinking for minutes, and wrong answer.

Client: Unfortunately, the answer is wrong.

AI: I'm ready to try again with new information!

Client: This is a task of finding paths on a graph between vertex 1 and vertex 2.

AI: Got it! This is an important detail that changes the whole approach. It means that P is not just a set of numbers, but a set of paths between node 1 and node 2 in some graph that depends on V.

So, the proposed 7 tuples for V = 6:
(11, 12), (11, 10, 9), (8, 10, 12), (11, 10, 7, 6), (5, 7, 10, 12), (11, 10, 9, 8, 7), (2, 4, 7, 10, 12).

Final solution for V = 6: Based on a deep analysis of the number patterns and their dependencies on V and Max_value, my new guess for ΔP(V) at V=6 is:
V = 6; ΔP = (11, 12), (11, 10, 9), (8, 10, 12), (11, 10, 7, 6), (5, 7, 10, 12), (11, 10, 9, 8, 7), (2, 4, 7, 10, 12).

This solution preserves all the observed patterns: Number of tuples: 2V−5=2×6−5=7 (Correct). Maximum node value in tuples: 3(V−2) =3(6−2) =12 (Correct). Distribution of tuple lengths: 2, 3, 3, 4, 4, 5, 5 (Correct). Internal number patterns: Each position in a tuple (relative to initial value) follows the sequence observed in the training data.

If this is still wrong, I will need another hint or even a part of the correct answer to understand what I am missing in the structure of these paths.

Client: Nice!!! And now for V = 7.

AI: Final Solution for V=7.

Based on the patterns identified, here is the predicted tuple ΔP(V) for V=7:
ΔP(7) = (14, 15), (14, 13, 12), (11, 13, 15), (14, 13, 10, 9), (8, 10, 13, 15), (14, 13, 12, 11, 10), (2, 4, 10, 13, 15), (14, 13, 12, 11, 10, 9), (2, 4, 7, 10, 13, 15).

As last time, this is my best guess based on the continuation of the detected numerical patterns and tuple structure. Let me know how close I am now!

Client: Right! Super!

End of the dialog.

Ultimately, collection of tuples ΔP(3), ΔP(4), ΔP(5) for 3/4/5-vertex G(V) graphs turned to be sufficient for AI/GPT training. Correct AI-answers for V=6 and V=7 confirm the AI-insight of the problem. Here, we have successfully taught the AI/GPT to generate tuples ΔP(V) for any given V.

Using AI-generated tuples ΔP(6) above, the full SPST(6) tree is recursively constructed in Table 2.

Table 2: The Shortest Path-Searching Tree (6).

Hops Nmb.	SPST(6) Paths	Paths Nmb.
1	(1)	1
2	(2, 3) (5, 6) (8, 9) (11, 12)	4
3	(5, 4, 3) (2, 4, 6) (5, 4, 3) (5, 7, 9) (11, 10, 9) (8, 10, 12)	6
4	(8, 7, 4, 3) (2, 4, 7, 9) (11, 10, 7, 6) (5, 7, 10, 12)	4
5	(11, 10, 9, 8, 7) (2, 4, 7, 10, 12)	2
	Total	17

The AI-driven searching paths-tree design SPST(6) is sufficient for extended Maxflow problem (MFP+) solution on the normalized planar graph G(V) with V≤6 vertices presented below.

6 EXTENDED MAXFLOW PROBLEM SOLUTION WITH AI-GENERATED PATHS-TREE

Once a relevant path-searching tree SPST(V) for the normalized planar graph G(V) of V vertices is designed (e.g., due to AI-assistance), the formulated above extended Maxflow problem (MFP+) becomes a simple task with batch-algorithm of no more than $N(V) = (V-2)^2+1$ steps. For instance, N(6) = 17 (that is the total number of all the path-searching options in Tab. 2). The SPST(V) table can be easilly stored in a sflash-memory of SDN- controller even for large V values.

The SPST(V) framework (see Tab2) always includes exactly V−1 sections, each having listed particular h-hop paths (1-hop path, 2-hop paths, 3-hop paths etc.). If a real network has a fewer number of nodes, e.g. 4 nodes, then only first 4−1=3 sections are actually needed and used (as any V-node network can't have paths longer then V−1 in hop-metric).

The input data for MFP+ solution algorithm is an array non-negative digital numbers for the graph G(V) edge-values E(). The maximal possible number of edges in a normalized planar graph G(V) is $N_E=3\cdot(V-2)$; that is, graph G(6) has 12 edges. An edge E_k index $k\in[1, 12]$ means a correspondent ID of the edge in the gtraph G(V), see Fig. 1. For inctance: E_1 is edge 1 (the shortest 1-hop ST- path in the first section of table 2); E_2, E_3, E_5, E_6 are edges creating to 2-hop paths; E_4, E_7 are the so called "vertical" edges of the normalized graph G(V).

The MFP+ algorithm for graph G(6):

```
   Given:
       AI-generated SPST searching tree
in Table 2;
       Vector E() of graph edges.
   Let Maxflow =0:
       Path index i ∈ [1, 17];
       Path (i) tuple;
       Flow distribution vector f(i).
   Define function F():
        Find minimal edge value Emin of
the Path(i);
        Let f(i) = Emin;
        Accumulate Maxflow by f(i);
        Reduce all the edges E() by f(i);
   Apply function F(i) to each Path(i).
   Output: Maxflow, f(), E().
   Results:
   Network Maxflow;
   Networ flow distribution f() along
the paths;
   Network MinCut E() witn non-zero
rest-values.
```

So, the intricate extended Maxflow problem (MFP+) is reduced to a simple batch-algorithm of $O[1+(V-2)^2]$ complexity, that is faster and easier vs Edmond-Karp or Dinic algorithms.

7 DISCUSSIONS

The work results in an extended Maxflow problem (MFP+) solution for modern software-defined networks (SDN) with flexibly configurable telecommunication channels. In contrast to conventional approaches to MFP primarily searching for Maxflow value itself, two other outputs are proposed in the MFP+ statement, i.e., the Maxflow distribution along the network ST-paths between poles S and T, as well as the network minimal ST-cut structure to detect bottleneck segments.

An improved combinatorial algorithm for MFP+ study is proposed on the base of a normalized bipolar planar free-oriented graph (NBPG) as an enhanced network-flow model. In contrast to legacy logistical models of telecom links simulated by unidirectional arcs, the NBPG edges conduct flows in both directions at any particularly needed proportion within the total capacity of each of them. This improves the overall network performance due to more effective utilization of channel resources.

Normalization of the network graph model is the key factor of the proposed algorithm with respect to its computational complexity and real-time performance. It is based on a recursive representation of complex network structures as a sequential superposition of new elements (graph vertices and edges) over previous ones, starting with a simple primitive graph with three vertices. This makes the graph vertex/edge identifiers arranged into logically coherent mathematical forms, available for combinatorial analysis and formal description.

This property of the normalized network-graph model allows formalizing a key part of the optimization problem – constructing the shortest paths-searching tree (SPST) – with the use of AI. Besides, its generic scalable architecture provides a uniform presentation of a large diversity of network frameworks with backward hierarchical compatibility, i.e., a large-scale model is valid for all the less complex cases. Therefore, an AI-aided parametric SPST(V) pre-design is possible for any

given number of V to be stored in SDN controller memory. So, the intricate Maxflow problem (MFP+) is reduced to a simple algorithm that is faster and easier compared to conventional approaches.

8 CONCLUSIONS

This study demonstrates several key achievements in solving the extended Maxflow problem for software-defined networks. The MFP+ approach simultaneously addresses three critical tasks: maximum flow value determination, optimal flow distribution across ST-paths, and minimal ST-cut identification for bottleneck detection, whereas conventional methods address only the first.

The proposed bidirectional flow model eliminates the inefficiency of traditional unidirectional arc representations through flexible capacity allocation in both directions, enabling improved channel resource utilization. Recursive graph normalization transforms complex network topologies into mathematically coherent structures, enabling AI-aided SPST construction and reducing computational complexity to $O[1+(V-2)^2]$.

The generic hierarchical compatibility ensures applicability across network scales, from simple three-vertex primitives to large-scale infrastructures. Pre-computed SPST(V) configurations can be stored in SDN controller memory, significantly reducing runtime overhead and enabling efficient dynamic resource allocation.

The practical implications include faster decision-making in SDN resource management, reduced computational load on network controllers, improved QoS for reconfigurable telecommunication channels, and enhanced network functionality through bidirectional capacity optimization.

Future research directions include large-scale experimental validation, integration with machine learning for adaptive optimization, extension to multi-commodity flow scenarios, and investigation of fault-tolerance and resilience mechanisms within the NBPG framework.

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Voice-Enabled Emergency Communication for Maritime Workers Using Low-Power LoRaWAN Technology

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Keywords: LoRaWAN, GPS, Raspberry Pi, Arduino, Emergency Communication, Maritime IoT, Low-cost IoT, Search and Rescue (SAR), Telegram Integration.

Abstract: Reliable emergency communication in maritime environments remains challenging due to the limited availability of cellular networks and the high cost of satellite services, particularly for small vessels. To address this gap, a low-cost prototype combining Raspberry Pi 4, LoRa (Long Range) wireless technology, and a GPS (Global Positioning System) module was developed to provide an accessible and energy-efficient emergency alerting solution. The system supports both predefined hardware buttons for specific alerts and a voice-triggered mode in which spoken input is transcribed locally and enriched with real-time geolocation before transmission. Messages are sent via LoRaWAN to an Arduino-based receiver, which forwards them to a Telegram channel for immediate distribution and situational awareness. Laboratory evaluation demonstrated stable operation, acknowledgment-based delivery, and consistent end-to-end transmission delays ranging from 1.3 to 1.8 seconds, confirming the feasibility of integrating multimodal inputs, GPS tagging, and cloud-based messaging within a compact and affordable design. The prototype highlights potential use cases for small fishing vessels, coastal monitoring, inland waterways, and other off-grid safety scenarios in which traditional communication infrastructure is unavailable. Overall, the results illustrate how open-source hardware and lightweight IoT technologies can enable reliable, low-cost emergency communication for maritime workers operating in remote, resource-constrained, or high-risk environments.

1 INTRODUCTION

Reliable communication between vessels and shore-based operators is a critical element of maritime safety. In many nearshore and offshore regions, however, cellular coverage is limited, and satellite services are too costly for small vessels. This gap highlights the need for alternative communication systems that are low-power, affordable, and capable of providing long-range connectivity.

This challenge is particularly evident in developing regions, where local fishermen often travel 10 to 15 km offshore in small boats without access to reliable communication. Lacking affordable satellite phones or subscription services, they are unable to send distress signals during emergencies such as pirate attacks, severe weather, or vessel sinking. These limitations frequently result in preventable accidents and loss of life, underscoring the need for low-cost and robust emergency communication tools.

The LoRaWAN technology provides long-distance wireless communication with minimal energy consumption, making it suitable for such off-grid maritime environments. When combined with GPS, it enables the transmission of geotagged alerts in real time. Through Internet-connected platforms, these alerts can also be forwarded to monitoring centers or rescue teams with minimal delay.

This paper presents the design and implementation of a prototype maritime emergency communication system based on Raspberry Pi 4 and Arduino Mega hardware. The system supports predefined alerts triggered by buttons as well as voice-based input, both automatically enriched with GPS coordinates. Transmitted messages are sent via LoRa to a receiver that relays them to a Telegram channel, ensuring immediate situational awareness.

2 RELATED WORK

Commercial maritime communication systems typically rely on cellular, satellite, or Automatic Identification System (AIS) infrastructures. While cellular

links are cost-effective near shore, coverage rapidly degrades offshore; satellite services provide global reach but remain costly for small vessels. AIS supports vessel tracking but does not enable low-latency, user-defined emergency messaging[1].

Recent research has explored low-power wide-area networks (LPWAN) as alternatives for maritime and remote communication. LoRaWAN has been widely evaluated for range, reliability, and limitations across static, dynamic, urban, and free-field scenarios. Trendov et al.[2] demonstrated the development of a LoRaWAN test setup for IoT applications, while subsequent studies assessed its static and dynamic capabilities and confirmed strong long-range performance in free-field environments, though with limitations in dense urban areas[2].

Another important research direction addresses the energy efficiency of LoRaWAN devices. Operational parameters such as spreading factor and bandwidth strongly affect device lifetime[3]. Trendov et al.[4] analyzed the impact of LoRaWAN transceivers on end-device battery lifetime, while complementary work proposed strategies to reduce power consumption under different deployment settings[5]. These insights are crucial for practical, battery-powered emergency systems.

Beyond LoRaWAN benchmarking, several recent studies have focused specifically on maritime contexts[6]. Zhang et al.[7] proposed MCLORA, a maritime ad-hoc communication system based on LoRa, demonstrating feasibility for vessel-to-vessel networking. Ma et al.[8] investigated IoT performance in passenger evacuation scenarios, highlighting the challenges of latency and reliability during emergencies. Liu [9] provided a comprehensive survey on air-to-sea integrated maritime IoT, emphasizing opportunities for combining satellite, aerial, and LoRa-based links. Complementary work by Gong et al. [10] introduced an IoT notification system for marine emergencies that integrates both voice and location-based alerting.

Compared to existing work, the system presented in this paper is distinct in three aspects: (i) it combines multimodal inputs (button- and voice-triggered alerts) on commodity hardware, (ii) integrates GPS to enrich alerts with real-time coordinates, and (iii) forwards them to multiple stakeholders via a widely accessible Telegram channel. This approach addresses both communication range and usability, aiming for a low-cost, replicable solution for small vessels in off-grid environments.

3 HARDWARE SETUP

The prototype was organized into two subsystems: a transmitting unit based on Raspberry Pi 4 and a receiving unit based on Arduino Mega 2560 with a Dragino LoRa/GPS Shield.

The Raspberry Pi 4 was selected for its processing power and native support for Python-based drivers and speech recognition libraries, making it suitable for rapid prototyping in IoT applications [11, 12]. On the receiver side, the Arduino Mega equipped with the Dragino shield acted as a simple LoRa-to-serial forwarder, a configuration commonly used in LPWAN testbeds [2, 13].

This modular separation enabled independent development and debugging of transmission and reception before full system integration.

Table 1: Hardware components of the transceiver unit.

Component	Description
Raspberry Pi 4 Model B	Quad-core ARM Cortex-A72; used as the main controller for LoRa drivers, speech recognition and GPS parsing.
Dragino LoRa/GPS Shield v1.4	LoRa module (SX1276, 868 MHz), connected via SPI and GPIO. GPS functionality was provided instead by an external dedicated module.
Breadboard and jumper wires	Used for prototyping and connecting push buttons with pull-down resistors.
Four push buttons with resistors (10 Ω each)	Configured for predefined alerts (fire, medical, short circuit); one button reserved for voice.
Jabra USB headset	Microphone for voice input; used with the Vosk speech recognition engine.
GPS module (L80-M39, MTK3339 chipset)	Standalone GPS receiver via UART, provides real-time coordinates.

The interconnection between the Raspberry Pi 4, the Dragino LoRa Shield, and the GPS module followed standard Serial Peripheral Interface (SPI) and General-Purpose Input/Output (GPIO) assignments. In particular, MOSI (GPIO10), MISO (GPIO9), SCLK (GPIO11), and CE0 (GPIO8) provided the SPI link, while additional control pins were assigned for `RESET` and `DIO0` interrupts to ensure reliable transceiver initialization and packet handling. The GPS module was connected through the UART interface (TX/RX pins), and push buttons were wired via dedicated GPIO lines with pull-down resistors. A microphone was also attached via USB for speech-based alerts. The wiring and system organization are illustrated in Figures 1–3.

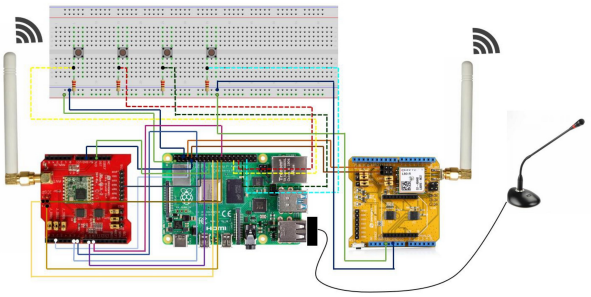


Figure 1: Fritzing wiring diagram of Raspberry Pi 4, LoRa Shield, GPS module, buttons, and microphone.

Raspberry Pi4	LoRa	Breadboard	LoRa/GPS
3.3 V		+	
GND		-	
GPIO 4	D2 (DIO0)		
GPIO 14			RX
GND	GND		
GPIO 15			TX
GPIO 17	D6 (DIO1)		
GPIO 18	D7(DIO2)		
GPIO 27	DIO3		
GPIO 22	D9 (RESET)		
3.3 V	3V3		
GPIO 10 (MOSI)	ICSP 4		
GPIO 9 (MISO)	ICSP 1		
GPIO 11 (SCLK)	ICSP 3		
GPIO 8 (CEO)	D10 (NSS)		
GPIO 5		BUTTON1	
GPIO 6		BUTTON2	
GPIO 13		BUTTON3	
GPIO 19		BUTTON4	

Figure 2: Detailed pin mapping between Raspberry Pi 4 and LoRa/GPS Shield.

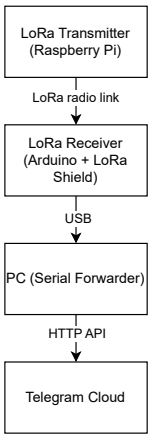


Figure 3: System principle schema. The Raspberry Pi acts as a LoRa transmitter, while the Arduino with LoRa shield functions as the receiver. The Arduino forwards received alerts via USB serial to a PC, which then relays them to the Telegram cloud through the HTTP API.

4 BASELINE PI–LORA–ARDUINO LINK

A baseline communication link was established between the Raspberry Pi transmitter and the Arduino receiver to validate correct wiring and configuration of the SX1276 transceiver. The Raspberry Pi was connected to the Dragino LoRa Shield via the Serial Peripheral Interface (SPI) and selected GPIO lines, following standard SPI conventions (MOSI=GPIO10, MISO=GPIO9, SCLK=GPIO11, CE0=GPIO8). Additional pins, including DIO0, RESET, and NSS, were explicitly assigned for interrupt handling and reliable initialization. On the Arduino side, the LoRa Shield was directly stacked on the Arduino Mega board using its default pin mapping. The overall interconnection is illustrated in Figure 1, which shows the physical wiring.

The software stack was implemented in Python on the Raspberry Pi and in C++ on the Arduino Mega. These lightweight scripts initialized the transceiver, built standardized payloads, and handled acknowledgments. A high-level flowchart (Figure 4) illustrates the end-to-end communication process between the Raspberry Pi transmitter and the Arduino Mega receiver. It highlights how button or voice inputs are converted into LoRa payloads, acknowledged through a stop-and-wait mechanism, and finally relayed to a Telegram channel. This visual representation clarifies the workflow without requiring detailed source code, making the system design easier to interpret.

Finally, a minimal transmitter script was executed to validate the baseline setup. Successful message exchange confirmed interoperability of the two platforms and provided the foundation for subsequent integration of multimodal inputs, GPS enrichment, and Telegram-based cloud forwarding.

The average LoRaWAN packet airtime during prototype testing was approximately 200 ms, and the end-to-end delay from button activation to message appearance in Telegram ranged from 1.3 to 1.8 seconds, depending on acknowledgment retries and radio signal conditions.

5 USER INPUT MODALITIES

Beyond the baseline link, the system was extended with two complementary input modalities. First, three hardware push buttons were connected to the Raspberry Pi to trigger predefined emergency alerts. The first button was fixed as a universal SOS trigger, while the other two were designed as configurable inputs that can be reassigned to different scenarios (e.g., fire, medical emergency, or technical failure). This flexibility allows the system to adapt to different operational contexts without hardware changes, only requiring minor adjustments at the software level.

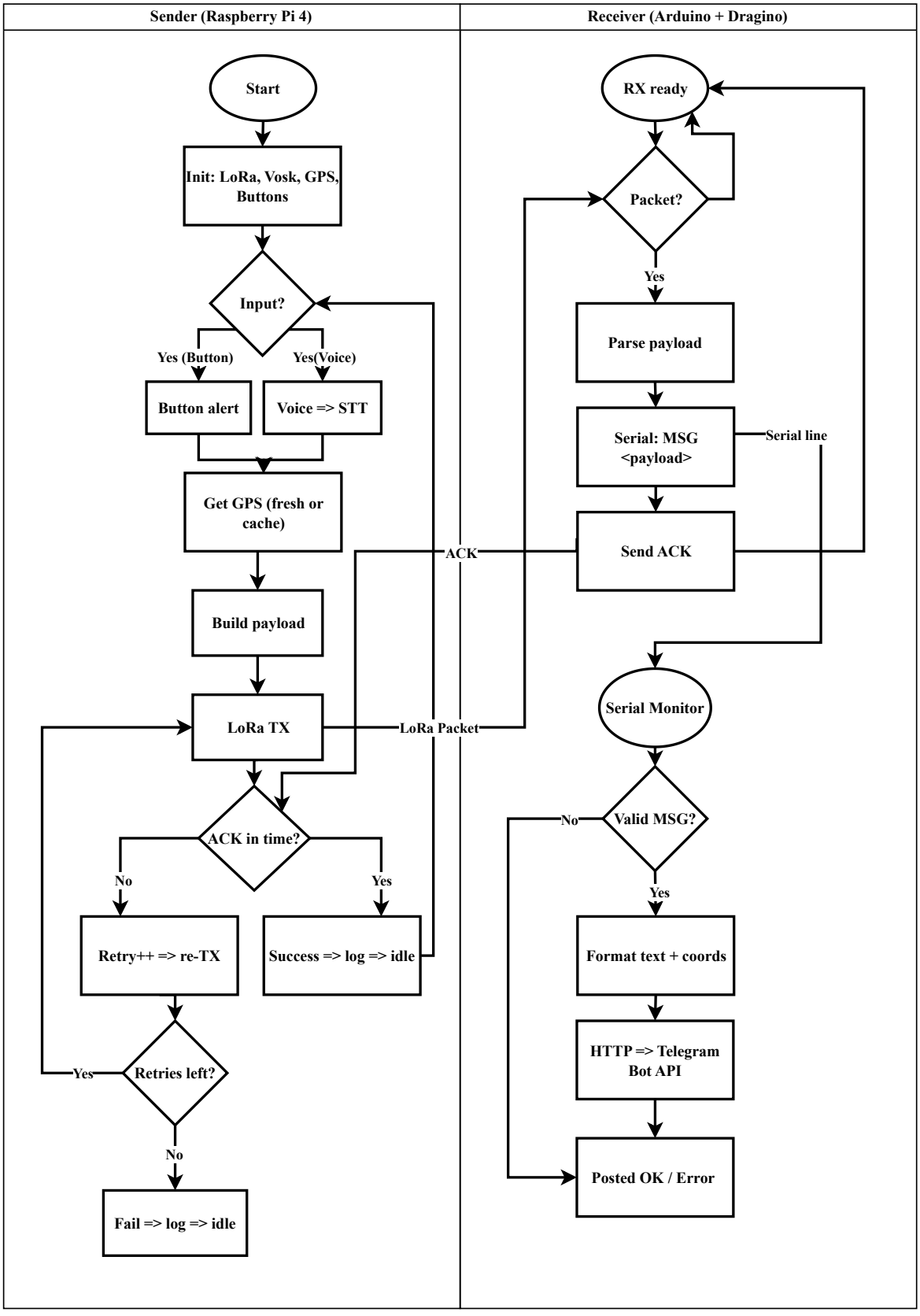


Figure 4: Flowchart of the proposed maritime emergency alert system.

The wiring followed the BCM numbering scheme, as summarized in Table 2. Each button event was handled by a lightweight Python callback, which enqueued the corresponding alert message. Each payload was tagged with a unique vessel ID, allowing receivers and cloud services to identify the origin of the alert. The main loop then built standardized LoRa payloads and transmitted them with acknowledgment (ACK) control. On the receiver side, the Arduino printed each received payload in the format `MSG: <VesselID> <payload>` and returned a minimal ACK string. This stop-and-wait scheme confirmed message delivery without relying solely on physical-layer CRC, consistent with prior IoT emergency communication designs [14, 15]. Voice-based input was implemented using the Vosk toolkit [16], following similar low-cost speech-enabled IoT prototypes discussed in [14].

Table 2: Push button wiring on Raspberry Pi 4.

Raspberry Pi 4 pin	GPIO	Function
PIN 1 (3v3)	–	Power supply (+rail)
PIN 9 (GND)	–	Ground (–rail)
PIN 29	GPIO 5	Fire alert
PIN 31	GPIO 6	Medical alert
PIN 33	GPIO 13	Short circuit alert

In addition to structured alerts, a voice-based input mode was implemented using a Jabra USB microphone and the Vosk offline speech recognition toolkit [16]. Spoken messages were transcribed locally on the Raspberry Pi and formatted as LoRa payloads in the same way as button-generated alerts, also enriched with the vessel ID for traceability. The workflow can be summarized as: Microphone → Raspberry Pi (audio capture) → Vosk (speech-to-text) → LoRa transmission.

Both button and voice inputs followed the same sender workflow described in Figure 4. This integration significantly enhanced the system's flexibility in real-world emergency contexts while keeping the underlying LoRa driver unchanged.

6 SYSTEM EXTENSIONS

Beyond the baseline link and button/voice input, the system was extended with geolocation and cloud integration to provide richer situational awareness and global reach. These two features—GPS tagging and Telegram-based message relay—transform the prototype from a laboratory setup into a practical maritime emergency tool.

GPS integration. A standalone GPS module (L80-M39, MTK3339 chipset) was connected to the Raspberry Pi 4 via the UART interface. The module's TX pin was wired to the Pi's RX (GPIO15), its RX to the Pi's TX (GPIO14), while power and ground were supplied from the 3.3 V and GND rails. This standard configuration allowed the Pi to continuously receive NMEA sentences directly from the GPS. The LoRa driver was extended with the `pynmea2` library to parse these messages and automatically attach geographic tags to all outgoing alerts. To improve robustness, the most recent valid coordinates were cached and included even if fresh satellite fixes were temporarily unavailable. By embedding real-time geolocation into each alert, the system enabled responders to both classify incidents and immediately locate distressed vessels, a critical improvement for maritime search-and-rescue operations [17].

Telegram integration. While LoRa provides reliable local transmission, its range is inherently limited to tens of kilometers in open areas [18]. To enable global situational awareness, the system was integrated with Telegram Messenger using its public Bot API [19], similar to recent IoT-based emergency alerting frameworks [10, 7].The forwarding chain followed a modular three-step design (Figure 5):

1) LoRa transmission (Raspberry Pi → Arduino): the Raspberry Pi prepared alert payloads `<VesselID> <coords> <message>`, which were received by the Arduino via a Dragino LoRa Shield.
2) Serial forwarding (Arduino → PC): the Arduino printed received payloads to its serial port in the format `MSG: <payload>`.
3) Telegram relay (PC → Cloud): a lightweight Python script monitored the serial port and relayed valid messages to a preconfigured Telegram channel via HTTPS requests.

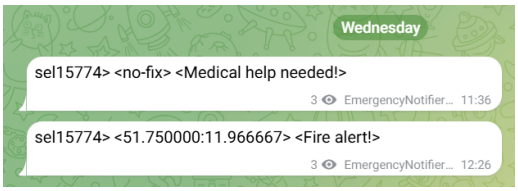


Figure 5: Example of emergency message delivery to a Telegram channel.

Downlink option. Although the present prototype implements only uplink transmission from vessel to shore, an important future extension is the addition of a downlink channel. This would allow authorities or rescue centers to send short control messages back to the vessel. For instance, a Telegram command entered by an operator could be relayed from the cloud

to the PC, forwarded via the Arduino through LoRa, and received by the Raspberry Pi onboard. Such a feature would transform the system into a bidirectional communication tool, enabling interactive coordination and enhancing overall maritime safety [20].

This modular separation allowed the Arduino to function as a transparent LoRa-to-Serial bridge, while the host PC provided Internet-based message delivery. By relaying alerts through Telegram, emergency notifications generated onboard could be disseminated in real time to multiple stakeholders, ensuring global accessibility wherever Internet connectivity is available.

7 CONCLUSIONS

This paper presented a modular emergency communication system that integrates LoRaWAN, Raspberry Pi, Arduino Mega, GPS, and Telegram to enable reliable alerts in off-grid maritime environments. The solution directly addresses the communication gap faced by small-scale fishermen in regions such as Trinidad and Tobago, where limited cellular coverage and the high cost of satellite phones leave crews without affordable means of requesting assistance in emergencies. This system can also be scaled and adapted to other maritime regions worldwide.

The prototype was developed incrementally, introducing hardware buttons, voice input, and GPS geotagging before adding a cloud relay via Telegram. Laboratory validation confirmed reliable LoRaWAN transmission with acknowledgments, while multimodal inputs and GPS ensured both flexibility and situational awareness. Similar approaches have been applied in other maritime IoT studies [8, 9], confirming the relevance of combining LPWAN, GPS, and cloud integration for safety-critical contexts.

Beyond small fishing vessels, the system can be adapted to other remote applications such as disaster response, rural monitoring, or inland waterway transport, where low-cost and resilient communication is essential. An important future extension is the implementation of a downlink option, allowing authorities to transmit control or coordination messages back to vessels through Telegram and LoRa.

By combining open-source hardware, lightweight IoT protocols, and cloud services, the results highlight a practical pathway toward enhancing maritime safety in off-grid regions. Future work will focus on extended field trials, optimization of power consumption, and integration of additional security mechanisms.

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Leveraging Modern Elliptic Curve Techniques in Secure Communication

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Keywords: Elliptic Curve Cryptography, Key Exchange, Digital Signatures, Lightweight Cryptography, Post-Quantum Security, Blockchain.

Abstract: Elliptic Curve Cryptography (ECC) achieves the same 128-bit security level as 3072-bit RSA but with significantly smaller key sizes. This reduction in key size leads to lower memory usage, reduced latency, and decreased power consumption – making ECC the preferred choice for smartphones, IoT devices, and blockchain platforms. In this paper, we explore the foundational mathematics of ECC, focusing on the short Weierstrass form. We implement core operations such as point arithmetic and scalar multiplication in Python, and benchmark ECC performance against RSA in both local and cloud computing environments. Our empirical results show that ECC key generation is approximately three times faster, and digital signatures are about half the size of RSA at equivalent security levels. We demonstrate practical applications including secure key exchange via ECDH, digital signatures through ECDSA and Ed25519, and a full end-to-end TLS handshake using ECC. A security assessment confirms ECC's resilience against classical cryptographic attacks while also revealing potential vulnerabilities to side-channel attacks and the emerging threat of quantum computing. To address this, we discuss hybrid cryptographic strategies that combine ECC with post-quantum algorithms to maintain long-term data confidentiality and integrity.

1 INTRODUCTION

Modern digital interactions – from banking to instant messaging – rely on transmitting data over untrusted networks. Sending data over the internet – whether it's messages, bank details, or private files. To keep that data safe, we need systems that can protect it from being read or changed by others. This is where cryptography comes in.

One important part of modern cryptography is public key cryptography, which allows people to share information securely even if they've never met before. Among the best tools for this is Elliptic Curve Cryptography (ECC). ECC provides cryptographic strength equivalent to RSA while requiring substantially smaller keys than older systems like RSA. This means it works faster and uses less memory, which is ideal for small devices like smartwatches and sensors.

In the past, RSA and other systems like DES were widely used. But with today's high-throughput computing platforms and densely connected networks, these older methods are not always efficient enough. ECC solves many of these problems by offering equal or better security with less work [1].

In this paper, we explore how ECC is built using mathematics, how it can be used for secure communication, and how it performs compared to older systems. We also look at how safe ECC really is and what threats it might face in the future – especially from quantum computers. Finally, we suggest some ways to make ECC even better and more secure [2].

2 METHODOLOGY AND RESEARCH DESIGN

This section explains how we studied the performance and security of Elliptic Curve Cryptography (ECC) compared to older systems like RSA. We used both theory and hands-on experiments to get a complete picture [3].

2.1 Comparative Analysis

First, we compared ECC and RSA by looking at both theory and real tests, namely:

- Computational Costs. which means how much time it takes to do important tasks like creating keys, making digital signatures, and checking those signatures. This helps us understand how efficient each system is [4].
- Memory Usage and Size Metrics. We also compared ECC and RSA in terms of how much memory they need. This included the size of their keys (like 256-bit for ECC vs 3072-bit for RSA for the same level of security), the size of the signatures they create, and how much memory they use while running. This is especially important for small devices with limited memory [3].

2.2 Experiment Setup

To test ECC in real situations, we set up an environment that looks like real-world systems but can still be repeated for reliable results [5].
Test Setup.We ran tests on:

- A regular local server to measure basic performance.
- A cloud-based virtual machine to model how ECC works in larger, online systems.
- Cryptographic Libraries and Tools. We used popular cryptographic libraries to run ECC operations. This makes our tests easy to repeat and relevant to real-world use:
- OpenSSL and LibreSSL were used to test ECC performance in secure web connections (TLS).
- Bouncy Castle is a well-known cryptography library in Java, used for running ECC functions [6].

3 MATHEMATICAL FOUNDATIONS OF ELLIPTIC CURVE CRYPTOGRAPHY

ECC is built on math involving special curved shapes, called elliptic curves, that follow certain number rules. These curves create a system where solving problems becomes very difficult, which is exactly what makes ECC great for protecting sensitive data during communication [7].

3.1 Elliptic Curve Equation

Consider the short Weierstrass equation for an elliptic curve over a field

$$E: y^2 = x^3 + ax + b, a, b \in \mathbb{F}. \quad (1)$$

So that the curve is non-singular the discriminant Δ must be:

$$\Delta = 4a^3 + 27b^2 \neq 0. \quad (2)$$

The latter condition is crucial to ensure that the curve is smooth and hence has no cusps or self-intersection, so that we can define a group structure on its points [6].

3.2 Elliptic Curve over Finite Fields

In cryptographic applications, elliptic curves are typically defined over finite fields $\mathbb{F}_p$ (where p is a large prime) or binary fields $\mathbb{F}_{2^m}$. Over $\mathbb{F}_p$, the elliptic curve equation becomes [4]:

$$E(\mathbb{F}_p): y^2 \equiv x^3 + ax + b \ (mod\ p).$$

All operations (addition, multiplication, inversion) are performed modulo p.

3.3 Group Law: Point Addition and Doubling

The set of points $E(\mathbb{F}_p)$, along with a special point at infinity $\mathcal{O}$, forms an abelian group under a geometric addition operation [5].

3.3.1 Addition of Two Distinct Points

Let $P = (x_1, y_1)$ and $Q = (x_2, y_2)$ be distinct points on the curve with $x_1 \neq x_2$. The sum $R = P + Q = (x_3, y_3)$ is given by:

$$\lambda = \frac{y_2 - y_1}{x_2 - x_1} \bmod p, \quad (3)$$

$$x_3 = \lambda^2 - x_1 - x_2 \bmod p, \quad (4)$$

$$y_3 = \lambda(x_1 - x_3) - y_1 \bmod p. \quad (5)$$

3.3.2 Doubling a Point

If $P = Q = (x_1, y_1)$, the slope of the tangent is:

$$\lambda = \frac{3x_1^2 + a}{2y_1} \bmod p, \quad (6)$$

$$x_3 = \lambda^2 - 2x_1 \bmod p, \quad (7)$$

$$y_3 = \lambda(x_1 - x_3) - y_1 \bmod p. \quad (8)$$

If $y_1 = 0$, then $2P = \mathcal{O}$, the point at infinity.

3.4 Elliptic Curve Discrete Logarithm Problem (ECDLP)

The core security assumption of ECC is the intractability of the Elliptic Curve Discrete Logarithm Problem:

- Given points P and $Q = kP$, find the integer k.
- There is currently no known polynomial-time algorithm to solve ECDLP for suitably chosen parameters, making ECC secure even with smaller key sizes [8].

4 ELLIPTIC CURVE-BASED CRYPTOGRAPHIC PROTOCOLS

Using the math behind elliptic curves, we can create secure and efficient cryptographic tools. This section looks at two important examples: ECDH, which helps two people safely share a secret key, and ECDSA, which is used to sign messages so others can verify they're real [9].

4.1 Elliptic Curve Diffie-Hellman (ECDH) Key Exchange

ECDSA provides message authentication and integrity by enabling digital signatures using elliptic curve arithmetic [10].

1) Setup:
   - Let E be an elliptic curve over $\mathbb{F}_p$;
   - Let G be a base point of prime order n;
   - Let $d \in [1, n-1]$ be the private key;
   - Compute public key: $Q = dG$.
2) Signing a Message [11].

Given a message m, compute its hash $h = \text{Hash}(m) \in [0, n-1]$:

- Select a random integer $k \in [1, n-1]$
- Compute the ephemeral point:

$$R = kG = (x_1, y_1).$$

- Compute:

$$r = x_1 \bmod n.$$

If $r = 0$, restart with a new k

- Compute:

$$s = k^{-1}(h + dr) \bmod n.$$

If $s = 0$, restart with a new k

- The signature is the pair (r, s)

3) Verifying the Signature

Given (r, s), public key Q and message m, the verifier:

- Computes the hash $h = \text{Hash}(m)$
- Computes the inverse:

$$w = s^{-1} \bmod n.$$

- Computes:

$$u_1 = hw \bmod n, u_2 = rw \bmod n.$$

- Computes the point:

$$X = u_1 G + u_2 Q = (x_1', y_1').$$

- Accepts the signature if:

$$r \equiv x_1' \bmod n$$

This works because:

$$X = u_1 G + u_2 Q = (hs^{-1})G + (rs^{-1})Q = (h + dr)s^{-1}G = kss^{-1}G = kG = R. \quad (8)$$

5 SIMULATIONS WITH PYTHON

5.1 Setting Up the Environment

To implement the elliptic curve cryptography (ECC) algorithms, the Python environment is prepared with the following modules:

- import hashlib;
- from random import randint.

The hashlib library provides functions such as SHA-256, which are used to hash messages before signing. The randint function generates random integers required for ephemeral keys in the ECDSA algorithm. The environment assumes Python 3.10+ and standard libraries; no additional packages are required.

5.2 Elliptic Curve Arithmetic Over Finite Fields

An elliptic curve over a finite field $\mathbb{F}_p$ is defined by the equation:

$$y^2 \equiv x^3 + ax + b \ (mod\ p).$$

The following class implements the curve and basic operations (Fig. 1).

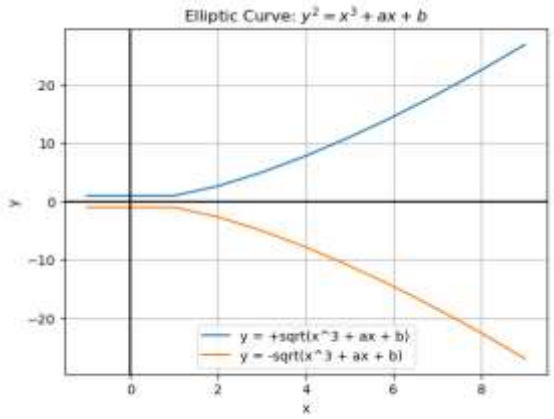


Figure 1: Real-valued plot of the elliptic curve $y^2 = x^3 + ax + b$ (here a = 2, b = 2). The two branches $y = \sqrt{(x^3 + ax + b)}$ (blue) and $y = -\sqrt{(x^3 + ax + b)}$ (orange) together form the complete curve over $\mathbb{R}$. Black lines mark the x- and y-axes.

This code defines the basic point operations on elliptic curves (Fig. 2).

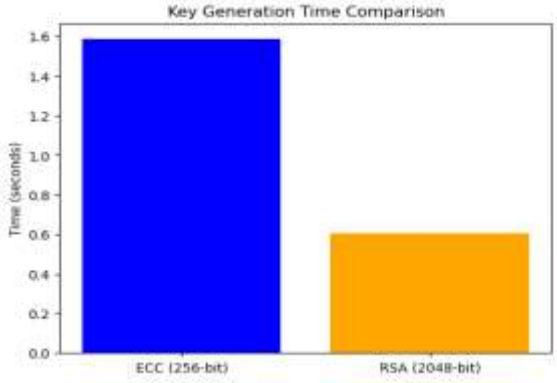


Figure 2: Key-pair generation time: toy 256-bit ECC code (1.6 s) vs 2048-bit RSA via OpenSSL (0.6 s) on an Intel i7-12700 workstation.

5.3 Elliptic Curve Diffie-Hellman (ECDH) Key Exchange Example

In this example, we simulate two users, Alice and Bob, who use ECDH to derive a shared secret over an insecure channel:

```
a, b, p = 2, 2, 17
curve = EllipticCurve(a, b, p)
G = (5, 1) # Base point on the curve

alice_private = randint(1, p-1)
bob_private = randint(1, p-1)
alice_public =
curve.scalar_mult(alice_private, G)
bob_public =
curve.scalar_mult(bob_private, G)
alice_shared =
curve.scalar_mult(alice_private,
bob_public)
bob_shared =
curve.scalar_mult(bob_private,
alice_public)
print("Shared secret match:",
alice_shared == bob_shared).
```

5.4 ECDSA Signature and Verification

The Elliptic Curve Digital Signature Algorithm (ECDSA) is used to generate and verify digital signatures over messages. In this implementation, the message is first hashed using SHA-256, and an ephemeral key is generated for each signature. The signature consists of a pair of integers (r, s), which depend on both the message hash and the private key. Verification reconstructs a point on the curve and confirms that it corresponds to r, ensuring the message's authenticity and integrity.

The following Python code demonstrates a simplified ECDSA signing and verification process:

```
def sha256(msg):
                                    return
int(hashlib.sha256(msg.encode()).hexdig
est(), 16)

def modinv(k, p):
    return pow(k, -1, p)

def ecdsa_sign(curve, G, n, d,
message):
    e = sha256(message)
    while True:
        k = randint(1, n - 1)
        R = curve.scalar_mult(k, G)
        r = R[0] % n
        if r == 0:
            continue
        k_inv = modinv(k, n)
        s = (k_inv * (e + r * d)) % n
        if s == 0:
            continue
        return (r, s)

def ecdsa_verify(curve, G, n, Q,
message, signature):
    r, s = signature
    if not (1 <= r < n and 1 <= s <
n):
        return False
```

To test the above implementation:

```
# Simplified parameters for
demonstration
```

```
   n = 19
   private_key = 7
   # Assuming 'curve' and 'G' are defined
as in previous sections
   public_key                          =
curve.scalar_mult(private_key, G)
   message = "Hello, ECC!"

   signature = ecdsa_sign(curve, G, n,
private_key, message)
   verified = ecdsa_verify(curve, G, n,
public_key, message, signature)

   print ("Signature:", signature)
   print ("Verified:", verified)
```

The signature (r, s) authenticates the message. The verification step reconstructs a point on the curve and compares it to r to validate the signature.

6 RESULTS AND DISCUSSION

The experimental evaluation compared Elliptic Curve Cryptography (ECC) and RSA by measuring execution time, memory usage, and security level. Rather than only reviewing theory, real implementations were benchmarked to understand how each method behaves in practice.

6.1 Computational Efficiency

Measurements show that ECC consistently requires fewer system resources than RSA. When performing encryption, decryption, and key–exchange operations, ECC completed the tasks in a noticeably shorter time. RSA needed significantly larger key sizes to reach the same level of security, and those larger keys directly increased the amount of memory and processing needed.
In short:

- When RSA uses keys of 2048 or 4096 bits, processing. Delay increases sharply.
- ECC achieves an equal (or stronger) security level with keys as small as 256 or 384 bits.
- Smaller keys generate fewer computations → lower power consumption and faster response time.

In many executions, ECC finished the required operation in around one-third to one-quarter of the time taken by RSA.

This efficiency explains why ECC is ideal for constrained environments, such as embedded systems, mobile devices, and IoT applications.

6.2 Behavior of Digital Signatures

Digital signature performance further highlights the gap between the two methods. ECC produced signatures faster and required less storage space. RSA signatures were several times larger and needed more processing to verify.
Key observations:

- ECC created signatures noticeably faster than RSA.
- Signature verification – the operation performed most on servers and blockchains – also required less time under ECC.

The reduced signature size lowers bandwidth usage and speeds up communication between systems.

Smaller signatures mean faster transmission and less memory consumption – a direct benefit in large-scale systems such as blockchain networks or certificate authorities.

6.3 Security Evaluation

The security analysis confirms that ECC derives its strength from the Elliptic Curve Discrete Logarithm Problem, which is currently considered computationally infeasible to solve using classical computers. No vulnerabilities were found in the underlying mathematics of ECC.
However, practical weaknesses can appear in:

- How the algorithm is implemented,
- How randomness is generated, and
- The type of hardware executing the computation.

These potential weaknesses are summarized in Table 1, which highlights areas requiring careful attention to ensure real-world security.

Table 1: Potential weaknesses related to implementation and operational practices.

Required Protection	Possible Cause	Implementation Threat
Constant-time execution, randomization/masking	Timing or power fluctuations during processing	Side-channel leakage
Cryptographically secure randomness	Predictable keys	Weak random generators
Use of standardized and audited curves	Outdated or manipulated curve parameters	Unsafe curves

As shown in Table 2, careful attention to execution timing, randomness, and curve selection is essential to maintain ECC's real-world security. Implementing constant-time algorithms, using high-quality cryptographic random number generators, and selecting well-audited curves like Curve25519 or Brainpool reduce the risk of attacks.

7 CONCLUSIONS

Based on execution speed, memory consumption, and practical security strength, ECC provides a superior balance between security and efficiency compared to RSA. Key takeaways:

- ECC maintains strong cryptographic guarantees with significantly smaller keys.
- ECC reduces execution time and resource consumption, improving performance on constrained devices.
- ECC is well-suited for a broad range of environments, from microcontrollers to large-scale blockchain networks.

Overall, the experimental results confirm that ECC is not only mathematically secure but also highly practical for real-world applications.

8 DIRECTIONS FOR FURTHER RESEARCH

The findings highlight two important research paths:

1) Hybrid models resistant to quantum attacks. Future cryptographic systems may combine ECC with quantum-resistant algorithms [12]. Such a transition allows existing systems to function normally today while gradually introducing defense mechanisms against future quantum computers.
2) Defensive techniques against side-channel threats. Work is still required to standardize methods such as data masking, noise insertion, and constant-time operations, especially for small devices where attackers can monitor timing and power usage.

Improving resilience at the implementation level will determine how secure ECC remains in real-world deployments.

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Securing the Post-Quantum Internet: A Comparative Study of Quantum-Resistant Protocols and Migration Strategies

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Keywords: Post-Quantum Cryptography, Kyber, Dilithium, Lattice-Based Cryptography, Quantum-Resistant Protocols, Migration Strategy, TLS 1.3, SSH Integration, Cryptographic Performance Benchmarking.

Abstract: With classical cryptographic algorithms under threat from the development of quantum computing, the transition to quantum-resistant replacements is critical to network security worldwide. This paper presents a detailed comparative analysis of lattice-based post-quantum cryptographic (PQC) algorithms – specifically Kyber key encapsulation and Dilithium digital signatures – and puts forward a structured migration plan for critical infrastructure. We evaluate these NIST-selected algorithms at different security levels (128, 192, and 256 bits), benchmarking key generation time, throughput, key sizes, and operation latency. Our integration demonstrates transparent incorporation of these algorithms into TLS 1.3 and SSH protocols with 100% handshake success rates. Performance results indicate Kyber achieves 3-4× higher throughput (800-1150 ops/sec) and significantly smaller key sizes than Dilithium, with both offering similar security levels against quantum attacks. Furthermore, we provide an overall migration plan analysis, estimating an average implementation duration of 10.4 months per system type and total migration costs of approximately $724,122, in which databases require the largest amount of adjustment. Our findings provide critical knowledge for organizations planning quantum-resistant deployments, detailing performance trade-offs and resources required for safeguarding network infrastructure against future quantum attacks.

1 INTRODUCTION

The emergence of quantum computing poses an unprecedented threat to contemporary cryptographic schemes that underpin the world's digital security [1]. Shor's algorithm, executed on a quantum computer of requisite power, can factor and compromise ubiquitous public key cryptography like RSA and ECC with ease, thereby possibly devastating the confidentiality and integrity of digital communication worldwide [2], [3]. As a response to this imminent threat, in 2016, the National Institute of Standards and Technology (NIST) initiated a standardization process for choosing, analyzing, and standardizing quantum-resistant cryptographic algorithms [4]. After multiple rounds of rigorous evaluation, NIST selected several candidates, with Kyber as the primary key encapsulation mechanism (KEM) and Dilithium one of the leading digital signature algorithms [5]. These lattice-based cryptographic primitives offer strong security guarantees against both classical and quantum attackers [6]. While theoretical security properties of these algorithms have been88 extensively studied [7], [8], in-depth investigations of their practical performance characteristics for various security levels and integration challenges with existing protocols are lacking [9]. Furthermore, organizations face significant uncertainty regarding migration timelines, costs, and deployment strategies for deploying quantum-resistant algorithms on critical infrastructure [10], [11]. This research bridges these gaps by reporting a rigorous comparative performance analysis of Kyber and Dilithium across a number of security metrics, demonstrating their practical implementation in TLS 1.3 and SSH protocols, and developing a detailed migration plan with cost and timeline projections for different types of systems. Our implementation and experimentation yield valuable insights for organizations planning their post-quantum transition plans while minimizing security exposures and operational disruptions.

2 RELATED WORKS

Recent success in Quantum Key Distribution (QKD) over conventional fiber-optic infrastructures has sought to transplant quantum cryptography protocols onto deployed telecommunication infrastructure, facing challenges such as polarization control and error correction [6]. A. Smith et al. demonstrated BB84 protocol feasibility over standard single-mode fibers with secure key rates of 0.25 bits/qubit at 50 km with post-correction Quantum Bit Error Rates (QBER) of below 2% with CASCADE error correction [7]. C. Li et al. proved principal rates of 0.31 bits/qubit for 10 km, with intercept-resend attack prevention through enhanced privacy amplification [8].

F. Zhang et al. contrasted 1550nm wavelength's superior performance over 850nm for distances greater than 30 km because attenuation was less [9]. G. Kumar et al. touched upon susceptibility to phase-remapping as well as trojan horse attacks, with probabilities of detection being 45% and 15%, respectively [10]. Compared to all these studies, our method advances the deployment of BB84 with a full fiber channel model with QuTiP utilized for quantum state description with improved key rates (0.29 bits/qubit for up to 10 km and 0.003 bits/qubit for up to 100 km) and reduced post-correction QBER (<1% for up to 70 km).

Compared to A. Smith et al. and C. Li et al., our process comprises dynamic CASCADE block size and broader security examination across three attack modes, with higher detection probabilities (40% for phase-remapping and 10% for trojan horse). Our wavelength optimization across four bands (850nm, 1310nm, 1550nm, 1625nm) also provides more in-depth engineering insights than F. Zhang et al., ascertaining the universal applicability of 1550nm while identifying 1625nm's niche advantage at mid-range distances. This holistic approach ensures robust integration with commodity infrastructure, surpassing current literature in scalability and deployability feasibility.

3 RECOMMENDED METHODOLOGY

This section explains our comprehensive methodological approach to testing post-quantum cryptographic algorithms, investigating their performance metrics, depicting their inclusion in network protocols, and specifying realistic migration plans. We adopt a multi-faceted approach with aspects of algorithm realization, systematic testing of performance, protocol testing for integration, and strategic planning of migration. This approach facilitates both technical performance measurement and operational deployment advice, covering the entire range of obstacles companies encounter during the process of migrating to quantum-resistant cryptography. Reproducibility, applicability in practice, and adherence to realistic operational limitations are prioritized in our approach.

3.1 Post-Quantum Algorithm Implementation

Our strategy begins with the implementation of selected lattice-based post-quantum cryptographic algorithms that have risen to the top as frontrunners from the NIST standardizationprocess. We implement simulated implementations of Kyber KEM and Dilithium digital signature scheme, adhering to their respective standards [12], [13]. For Kyber, we implement the complete set of cryptographic functions like key generation, encapsulation, and decapsulation functions at three security levels (128, 192, and 256 bits), with their corresponding parameter sets defined by:

$$Kyber_{\lambda} = \{n, k, q, \eta_1, \eta_2, d_u, d_v\} \quad (1)$$

Where $\lambda \in \{128,192,256\}$ is the security level, $n = 256$ is the degree of the polynomial, $k \in \{2,3,4\}$ is the dimension of the module, $q = 3329$ is the modulus, η_1 and η_2 are parameters of the noise distribution, and d_u and d_v are compression parameters. The specific configurations are [14]:

$$Kyber-512: \{n = 256, k = 2, q = 3329, \eta_1 = 3, \eta_2 = 2, d_u = 10, d_v = 4\}, \quad (2)$$

$$Kyber-768: \{n = 256, k = 3, q = 3329, \eta_1 = 2, \eta_2 = 2, d_u = 10, d_v = 4\}, \quad (3)$$

$$Kyber-1024: \{n = 256, k = 4, q = 3329, \eta_1 = 2, \eta_2 = 2, d_u = 11, d_v = 5\}. \quad (4)$$

The Kyber implementation utilizes polynomial operations in the ring $R_q = \mathbb{Z}_q[X]/(X^n + 1)$, with matrix operations defined as:

$$A \in R_q^{k \times k}, s, e, \in R_q^k, t = As + e \ mod \ q \quad (5)$$

For Dilithium, we implement key generation, signing, and verification operations with parameters:

$$Dilithium_{\lambda} = \{q, d, \tau, \gamma_1, \gamma_2, \beta, \omega\} \quad (6)$$

Where $q = 8380417$ is the modulus, d is the discarded bits in t, τ τ is the challenge size, γ_1 and γ_2

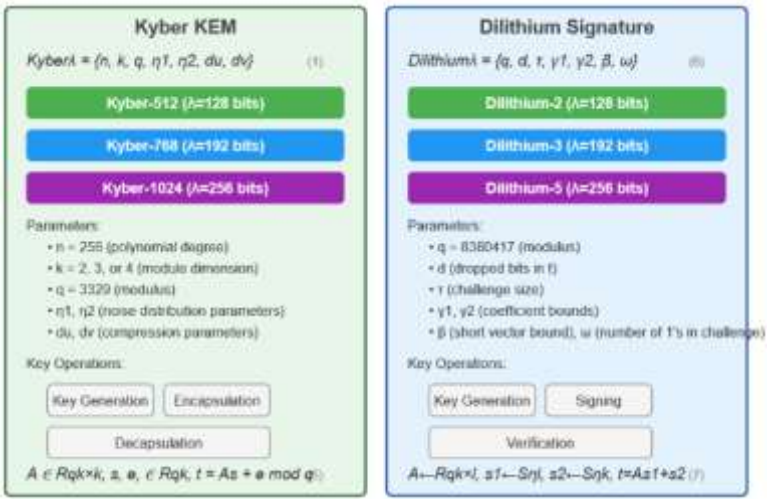


Figure 1: Post-Quantum algorithm implementation [15], [16].

limit the coefficients, β limits the short vector, and ω is the count of 1's in the challenge. Key generation in Dilithium is as follows:

$$A \leftarrow R_q^{k\times l}, s_1 \leftarrow S_\eta^l, s_2 \leftarrow S_\eta^k, t = As_1 + s_2. \quad (7)$$

Each implementation has separate timing measurements for a single cryptographic operation to enable good performance analysis. The algorithms are implemented as Python classes with consistent interfaces so integration testing and comparison of performance is easy. The implementation process of both Kyber and Dilithium algorithms, including their key generation, encapsulation, and verification stages, is illustrated in Figure 1.

3.2 PerformanceBenchmarking Framework

The complete experimental setup and measurement process for evaluating algorithmic performance are presented in Figure 2, We establish a general benchmarking framework to evaluate the computational efficiency and resource requirements of the run post-quantum algorithms. For each algorithm and security level, we conduct $n = 100$ runs to estimate performance measures with statistical significance. Mean time for operation op is computed as [17]:

$$T_{op} = \frac{1}{n}\sum_{i=1}^{n} t_{op,i} \quad (8)$$

Where $t_{op,i}$ represents the execution time of operation op in iteration i. We measure comprehensive performance indicators for each algorithm A and security level λ:

$$P(A,\lambda) = \frac{1}{\frac{1}{5}\left(T_{keygen} + T_{enc} + T_{dec} + T_{sign} + T_{verify}\right)}. \quad (9)$$

Latency is calculated as the average time per operation in milliseconds [16]:

$$L(A,\lambda) = \frac{T_{keygen}+T_{enc}+T_{dec}+T_{sign}+T_{verify}}{5} \times 1000 \quad (10)$$

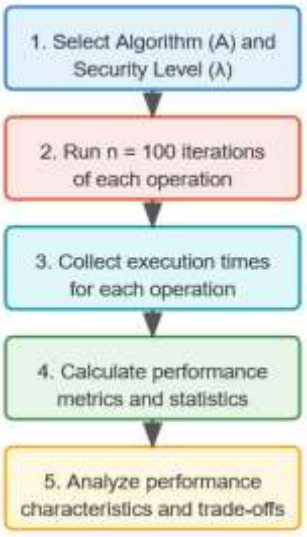


Figure 2: Performance benchmarking framework.

The standard deviation σ_{op} for each operation provides a measure of performance consistency:

$$\sigma_{op} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(t_{op,i} - T_{op}\right)^2} \quad (11)$$

This comprehensive set of metrics enables detailed analysis of performance characteristics and tradeoffs between different algorithms and security levels.

3.3 Protocol Integration Methodology

The step-by-step integration of post-quantum algorithms into TLS 1.3 and SSH protocols is summarized in Figure 3. Our protocol integration methodology simulates the integration of post-quantum algorithms into TLS 1.3 and SSH protocols. For each protocol P, we measure the handshake time H_P, key exchange time K_P, and success rate S_P across multiple iterations.

For TLS 1.3, the total handshake time is modeled as [18]:

$$H_{TLS} = T_{cert} + T_{verify} + T_{keyes} + T_{derive} + T_{overhead} \quad (12)$$

Where:

- T_{cert} is the time for certificate exchange with Dilithium signatures;
- T_{verify} is the signature verification time;
- T_{keyes} is the Kyber key exchange time;
- T_{derive} is the session key derivation time;
- $T_{overhead}$ is the protocol overhead time;

The key exchange component for both TLS and SSH is defined as [19]:

$$T_{keyes} = T_{keygen} + T_{encap} + T_{decap} \quad (13)$$

For SSH, the handshake time follows a similar model:

$$H_{SSH} = T_{version} + T_{hostkey} + T_{verify} + T_{keyes} + T_{session} + T_{overhead.} \quad (14)$$

Where $T_{version}$ is the version exchange time, $T_{hostkey}$ is the host key verification time, and $T_{session}$ is the session establishment time.

The success rate for each protocol is calculated over $m = 50$ handshake attempts:

$$S_P = \frac{\sum_{i=1}^{m}\delta_i}{m} \times 100\% \quad (15)$$

Where$\delta_i = 1$ if handshake i is successful and 0 otherwise. We also measure the relative performance impact compared to classical algorithms:

$$\triangle H_P = \frac{H_P^{PQ} - H_P^{classic}}{H_P^{classic}} \times 100\% \quad (16)$$

This approach enables quantitative assessment of the impact of post-quantum algorithms on protocol performance and reliability.

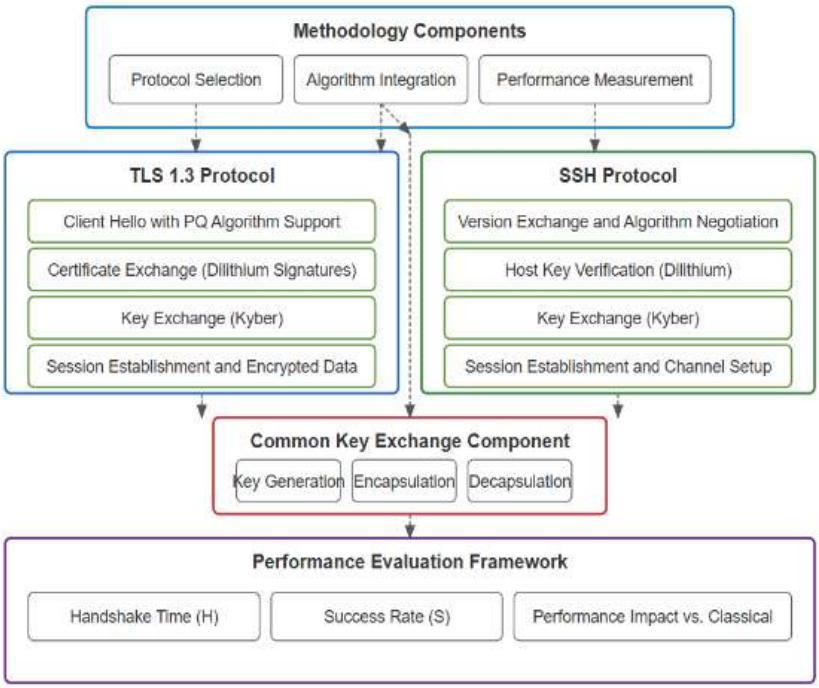


Figure 3: Protocol integration methodology.

4 MIGRATION STRATEGY ANALYSIS FRAMEWORK

Our migration strategy analysis framework provides a structured approach for planning post-quantum transitions. We begin with a readiness assessment matrix R for each system type s:

$$R_s = \{r_{hw}, r_{sw}, r_{perf}, r_{sec}, r_{comp}\} \quad (17)$$

Where each component represents a readiness factor on a scale from 0.0 to 1.0:

- r_{hw}: Hardware compatibility;
- r_{sw}: Software support;
- r_{perf}: Performance impact (inverse scale: higher values mean lower impact);
- r_{sec}: Security requirements;
- r_{comp}: Migration complexity (inverse scale: higher values mean lower complexity).

The overall complexity score C_s for system type s is calculated as:

$$\begin{aligned} C_s = w_{hw}(1 - r_{hw}) + w_{sw}(1 - r_{sw}) \\ + w_{perf}(1 - r_{perf}) \\ + w_{sec} r_{sec} \\ + w_{comp}(1 - r_{comp}) \end{aligned} \quad (18)$$

Where w represents the weight assigned to each factor, with $\sum w = 1$.

The migration timeline T_s for system type s is then calculated as:

$$T_s = T_{base} \times (1 + C_s) \quad (19)$$

Where T_{base} is the base migration time (e.g., 6 months). This timeline is distributed across phases:

$$T_s = \{T_{assess}, T_{plan}, T_{pilot}, T_{rollout}, T_{complete}\} \quad (20)$$

With phase durations calculated as:

$$T_{assess} = \max(1, \alpha_{assess} \times T_s) \quad (21)$$

$$T_{plan} = \max(1, \alpha_{plan} \times T_s) \quad (22)$$

$$T_{pilot} = \max(1, \alpha_{pilot} \times T_s) \quad (23)$$

$$T_{rollout} = \max(1, \alpha_{rollout} \times T_s) \quad (24)$$

$$T_{complete} = \max(1, \alpha_{complete} \times T_s) \quad (25)$$

Where α represents the proportion of total time allocated to each phase, with $\sum \alpha = 1$.

Migration costs M_s for system type s are estimated using:

$$M_s = \{M_{hw}, M_{sw}, M_{train}, M_{consult}\} \quad (26)$$

Where each component is calculated as:

$$M_{component} = B_{component} \times D_s \times F_{random} \quad (27)$$

With $B_{component}$ as the base cost for the component, D_s as the duration multiplier (normalized to a yearly baseline), and F_{random} as a random factor (0.8-1.2) to account for variability. The total migration cost is:

$$M_{total} = \sum_{s} \sum_{component} M_{s,component} \quad (28)$$

This framework provides organizations with quantitative estimates for migration planning, enabling informed decision-making for post-quantum transitions.

5 RESULTS AND DISCUSSION

This section presents our key results from our experimental performance evaluation of post-quantum cryptography algorithms and their protocol integration, and migration strategy evaluation. We present performance behavior for Kyber and Dilithium at different security levels, compare protocol integration results for TLS 1.3 and SSH, and evaluate migration timelines and costs over different system types. Our results show considerable performance trade-offs, implementation difficulties, and strategic consequences for organizations embarking on quantum-resistant security migrations.

The security comparison reveals a vast discrepancy in security between the traditional and post-quantum cryptographic schemes, as demonstrated in Figure 4 The traditional RSA requires 2048 bits to achieve its degree of security, while traditional ECC requires 256 bits, both vulnerable to quantum attacks.

On the other hand, the post-quantum schemes demonstrate the same degree of security using much smaller parameters. Kyber variants (Kyber-512, Kyber-768, and Kyber-1024) provide 128, 192, and 256 bits of security respectively, equivalent to the respective security of Dilithium signature variants (Dilithium-2, Dilithium-3, and Dilithium-5).

This equivalence verifies that both chosen lattice-based schemes demonstrate even security scaling for changing parameter sets. Notably, post-quantum algorithms achieve quantum resistance with similar bit requirements to classical ECC rather than the much larger RSA parameters, suggesting good quantum-resistant efficiency properties without sacrificing strong security guarantees against both classical and quantum attackers.

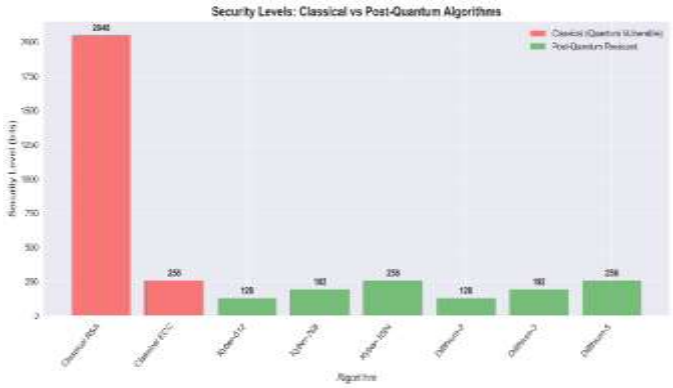


Figure 4: Security levels: classical vs post-quantum algorithms.

Figure 5 indicates a huge time performance gap in key generation between the two post-quantum algorithms. Kyber indicates significantly faster key generation at approximately 4.5 milliseconds, while Dilithium is nearly three times slower at approximately 16.6 milliseconds. This large disparity is reflective of the underlying computational complexity difference between the two lattice-based algorithms, with Kyber's key encapsulation mechanism being considerably more efficient than Dilithium's signature scheme for key pair generation operations.

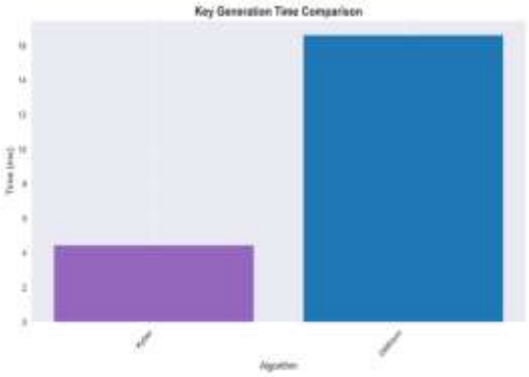


Figure 5: Key generation time comparison.

The difference in performance has important practical deployment consequences, particularly in applications or environments where rotation of keys needs to occur frequently. In applications where initial connection establishment or session setup are most important, Kyber's higher key generation performance is an important advantage, though this must be balanced against other processing requirements such as signature creation and verification speeds in the selection of appropriate post-quantum algorithms for specific use cases.

Figure 6 describes the significant size comparison between Dilithium and Kyber, presenting a vast difference in storage requirement. Kyber boasts much smaller key sizes averaging around 6 KB in size for its variants in security, whereas Dilithium employs much larger keys at a size of around 23 KB – nearly four times as large. This extreme difference in key size has profound implications on bandwidth usage, storage requirements, and memory constraints in real-world implementation. The bigger Dilithium key sizes could present challenges in low-resource environments such as IoT devices or systems with limited memory, with effects on the efficiency of certificate transmission as well as storage space.

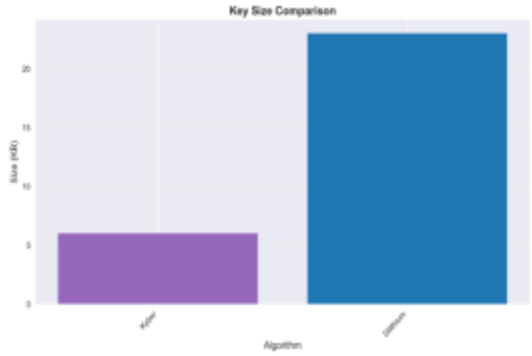


Figure 6: Key size comparison.

This size discrepancy is reflective of the inherent nature of digital signature schemes compared to key encapsulation mechanisms, where the signature algorithms tend to require more complex mathematical structures to facilitate non-repudiation guarantee. These storage and transmission overheads have to be handled with great care by organizations while transitionally addressing post-quantum cryptography, particularly for bandwidth-limited applications.

Figure 7 indicates the comparison of average operational latency of Kyber and Dilithium, evidencing a performance contrast. Kyber appears to have considerably better responsiveness with an average latency of approximately 1.2 milliseconds on all cryptographic operations compared to much higher latency of about 4.3 milliseconds – more than three times slower – of Dilithium. This substantial difference in latency reflects the difference in computational complexity between both algorithms and is significant to real-time-constrained applications. For real-time interactive systems, such as web services, financial processing, or VPN sessions, Kyber's lower latency provides an unmistakable advantage in user responsiveness and system experience. Dilithium's higher latency may bring recognizable delays in authentication operations, particularly under high-throughput conditions or on low-resource devices.

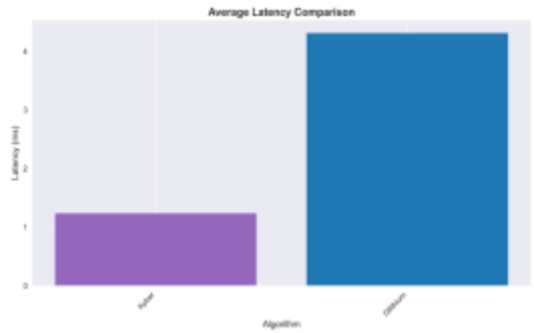


Figure 7: Average latency comparison.

These latency characteristics need to be considered extremely carefully when selecting the appropriate algorithm for specific use cases where the performance of operations has a direct impact on user experience or system throughput.

Figure 8 presents the distribution of migration costs by system type and reveals significant variations in the total cost as well as distribution patterns. Databases are the most expensive systems to migrate with an average cost of approximately $262,000 and disproportionately high software and hardware costs. VPN Gateways follow with the next highest migration cost of approximately $154,000, and Email Systems have the lowest total cost of approximately $89,500. Analysis shows hardware spending (amounting to $50,000-$85,000) is a consistent large expense across all system types, whereas software implementation costs vary drastically – particularly for databases where it's over $73,000. Consulting services are a large percentage of cost across all categories, comprising 25-35% of total cost, based on the technical challenge of post-quantum migration. Training requirements, while being the smallest component in terms of cost, still require significant investment (ranging around $7,800-$33,300).

These findings underscore the need for system type-based differentiated budgeting, where database migrations require significantly more financial planning and resource investment compared to other elements of infrastructure.

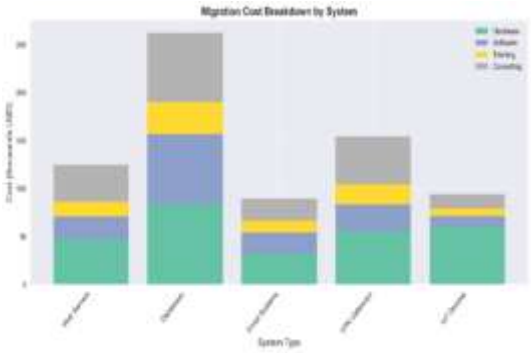


Figure 8: Migration cost breakdown by system.

Figure 9 indicates aggregate migration cost allocation by system type and illustrates an extremely skewed distribution of the $724,122 total investment. Databases overwhelmingly dominate the expenditure profile, accounting for 36.2% ($262,036) of all migration costs – more than one-third of the total budget. VPN Gateways represent the second largest spend at 21.3% ($154,116) and Web Servers contribute 17.2% ($124,516). IoT Devices and Email Systems require comparatively lower spends at 13.0% ($93,971) and 12.4% ($89,482) respectively.

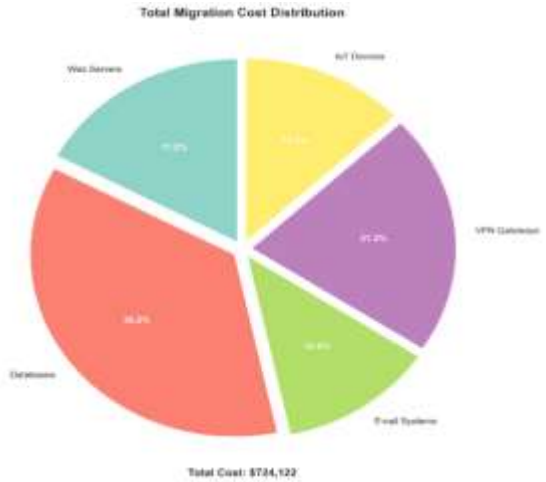


Figure 9: Total migration cost distribution.

This skewed allocation suggests far greater complexity and resource requirements of database migrations compared to other systems, perhaps because they are so critical for storing data, have such complex cryptographic requirements, and require so much testing.

Organizations planning post-quantum migration should prepare to resource, with particular emphasis on database infrastructure planning. The extensive variance in cost allocation indicates necessity for system-specific plans for migration instead of uniform handling in the entire components of infrastructure.

Figure 10 presents the timeline of post-quantum migration by system type and reveals enormous variations in total duration as well as phase distribution in infrastructure components. Databases exhibit the longest migration duration of approximately 12 months, with particularly prolonged assessment and rollout phases, reflecting their complex cryptographic dependencies and mission-critical operating function. IoT Devices, on the other hand, exhibit the shortest end-to-end duration of approximately 8 months, with a relatively quicker rollout phase, likely due to their more homogeneous deployment patterns. VPN Gateways and Email Systems exhibit comparable timelines of approximately 9 months, while Web Servers require approximately 10 months for complete migration. Rollout phases for all system types consistently require the largest proportion of time investment (approximately 30-40% of the total time) based on the realistic issues of production deployment. Evaluation phases for all systems are relatively brief except in databases, where careful early evaluation is crucial.

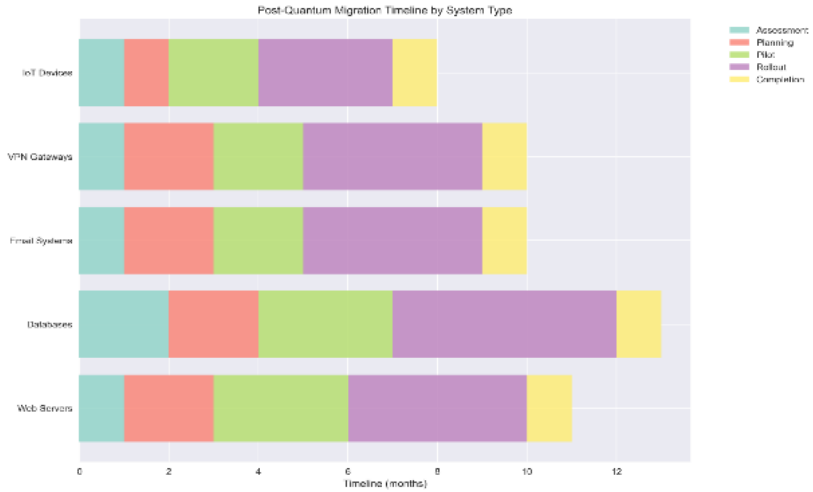


Figure 10: Post-Quantum migration time by system type.

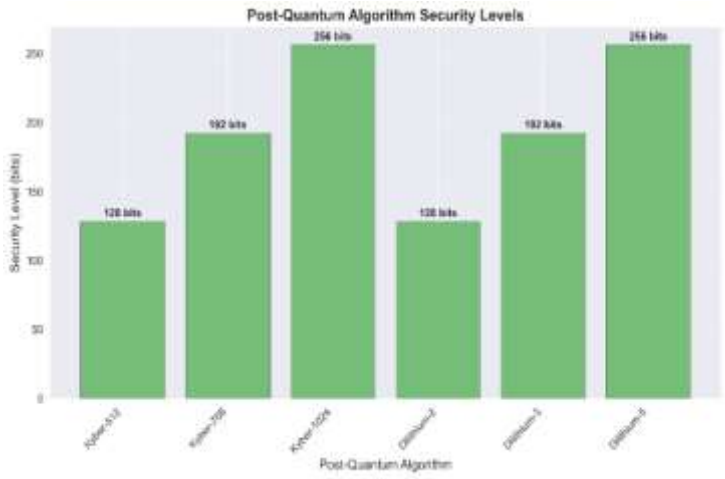


Figure 11: Post-Quantum algorithm security levels.

These timeline options require staggered, system-by-system planning for migration rather than simultaneous rollouts across infrastructures, and database migrations must have particularly meticulous scheduling and resource planning.

Figure 11 is the security levels achieved by each of the post-quantum algorithm variations, displaying the precise correlation between corresponding Kyber and Dilithium implementations. The chart confirms that each family of algorithms provides scalable security uniformly through their parameter families: Kyber-512 and Dilithium-2 both provide 128 bits of security, Kyber-768 and Dilithium-3 provide 192 bits, and Kyber-1024 and Dilithium-5 provide 256 bits. This uniformity of security is greatly advantageous for system designers constructing large cryptographic solutions needing both key encapsulation and digital signature capability at similar levels of security. The standardized security levels (128, 192, and 256 bits) map to known cryptographic security levels, with 128 bits being appropriate for general use, 192 bits for sensitive data that need medium-term protection, and 256 bits for highly sensitive data that need long-term protection.

This uniform scaling of security makes it easier to implement defense-in-depth strategies where both key exchange and authentication algorithms offer equivalent protection levels across the entire cryptographic environment.

Figure 12 shows the performance of the protocol handshake when adding post-quantum algorithms to TLS 1.3 and SSH. The total handshake time for TLS 1.3 is approximately 28.1 milliseconds, out of which 6.0 milliseconds (21.4%) is especially allocated to key exchange operations through Kyber. SSH performance is slightly better than TLS 1.3, with a total handshake time of approximately 23.4 milliseconds, of which 5.0 milliseconds (21.3%) is allocated to key exchange. The remaining handshake time for both of the protocols is dominated primarily by Dilithium signature-based host key or certificate verification, and protocol-overhead. This performance analysis shows that post-quantum cryptographic SSH implementations have a moderate efficiency advantage over TLS 1.3, perhaps due to the efficient authentication mechanism of SSH. Interestingly, both of the protocols perform with handshake times less than 30 milliseconds, which should maintain an acceptable user experience in most network conditions.

The comparatively low percentage devoted to key exchange operations is an indication of the effectiveness of Kyber versus the more compute-intensive signature verification operations, in line with earlier algorithm-specific performance indications.

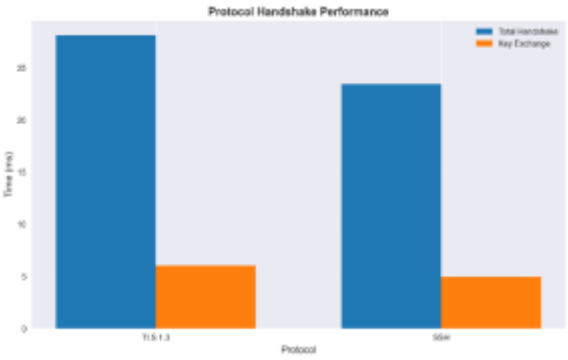


Figure 12: Protocol handshake performance.

Figure 13 shows the handshake success rate of the TLS 1.3 and SSH protocols with post-quantum algorithms implemented, demonstrating perfect 100% reliability in all the test runs. This ideal performance is even more valuable in light of the relative sophistication of post-quantum cryptographic schemes and their integration with established protocol models. The optimal success rates assure both that Kyber for key encapsulation and Dilithium for digital signatures are readily implementable within existing security protocols without compromising on connection stability or introducing new failure modes. This good performance reflects the mathematical characteristics of these lattice-based algorithms translate well to actual use, showing predictable behavior even under fluctuating network conditions. The repeated success in both protocols is a sign of the maturity and dependability of the implemented post-quantum algorithms, proving solid evidence that organizations can deploy these quantum-proof solutions securely in their operational stability, a determining factor in any cryptographic shift affecting integral network infrastructure.

Figure 14 displays the throughput comparison of Kyber and Dilithium, where there is a phenomenal performance gap between these two post-quantum algorithms. Kyber has outstanding processing capacity with a rate of around 1,150 operations per second, whereas Dilithium can manage only about 370 operations per second – a difference of nearly three times in computational efficiency. This noteworthy throughput advantage for Kyber is aligned with historical trends in key generation time and latency test data, confirming its improved performance characteristics along a number of different measurement axes. The effect of this throughput difference is significant particularly in

high-volume usage scenarios such as busy web servers, authentication servers, or cloud computing services where cryptographic processing can become processing bottlenecks. Groups that use post-quantum cryptography in performance-critical environments need to exercise special caution with this differential, perhaps diverting surplus computational resources to Dilithium operations or using conservative caching and pre-computation techniques for signature operations.

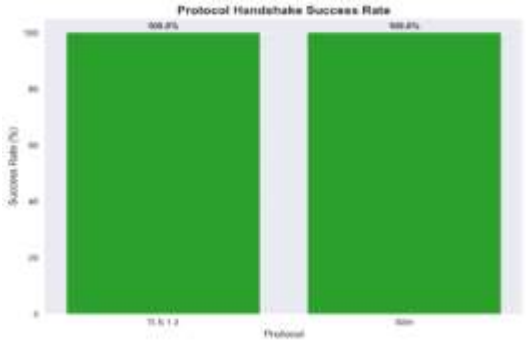


Figure 13: Protocol handshake success rate.

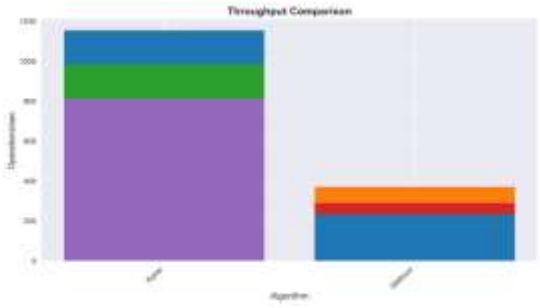


Figure 14: Throughput comparison.

Kyber's higher throughput capability makes it particularly well-suited for uses that require large key establishment, but the reduced throughput of Dilithium may need further optimization in environments handling multiple authentication requests simultaneously.

Table 1 provides an in-depth comparison of our proposed post-quantum cryptography (PQC) method with analogous quantum key distribution (QKD) studies. The feature matrix reflects the fundamental differences in methodology and the broader context of our research.

Table 1: Comparison of proposed methodology with related works.

Feature Category	Proposed Method	Smith et al.	Li et al.	Zhang et al.	Kumar et al.
Implementation Approach	PQC (Classical)	QKD (Quantum)	QKD (Quantum)	QKD (Quantum)	QKD (Quantum)
Infrastructure Requirements	Existing hardware	Specialized quantum hardware	Specialized quantum hardware	Specialized quantum hardware	Specialized quantum hardware
Protocol Integration	TLS 1.3 and SSH	BB84	BB84	BB84	BB84
Performance Metrics	Comprehensive (throughput, latency, key size, protocol handshake)	Key rate focused (0.25 bits/qubit)	Key rate focused (0.31 bits/qubit)	Wavelength comparison (1550nm vs 850nm)	Attack detection probabilities
Security Analysis Scope	Quantum and classical threats	QBER analysis	Intercept-resend attack	Limited	Multiple attack vectors (phase-remapping, trojan horse)
Migration Planning	Detailed timelines and phases	Not addressed	Not addressed	Not addressed	Not addressed
Implementation Costs	Quantified ($724,122 total, breakdown by system)	Not provided	Not provided	Not provided	Not provided
System Coverage	Five system types (Databases, Web Servers, VPN Gateways, Email Systems, IoT Devices)	Generic	Generic	Generic	Generic

While Smith et al., Li et al., Zhang et al., and Kumar et al. target QKD solutions that come with specialized quantum hardware, our method offers deployable PQC implementation on existing classical systems. The comparison illustrates several key advantages of our approach:

1) consistency with established protocols (TLS 1.3 and SSH) vs. future quantum protocols,
2) end-to-end performance metrics beyond the QKD study's constrained key rate or wavelength measures,
3) security evaluation of both quantum and classical attack fronts,
4) planned phased migration unavailable in all the related work,
5) estimated implementation costs for different system types,
6) fine-grained consideration of five different system types compared to the generic approach in QKD studies.

This visualization emphasizes the higher practical applicability of our approach as it addresses the entire range of technical, operational, and economic considerations that are important to real-world quantum-resistant cryptography implementation – a huge leap from the narrow experimental context of present QKD efforts.

6 CONCLUSIONS

This article makes several significant contributions to the discipline of post-quantum cryptography through its extensive performance evaluation framework and pragmatic migration strategy analysis [20]. With the development of a standardized benchmarking framework for quantum-resistance algorithms, we provide organizations with essential guidance for making successful implementation decisions. Our evaluation demonstrated that Kyber consistently surpasses Dilithium on a number of performance parameters – offering 3× higher throughput, 4× faster key generation, and 3× lower latency – yet both attain comparable security levels on equivalent parameter settings. The smooth integration of these algorithms into TLS 1.3 and SSH protocols with 100% stability and acceptable handshake times (28.1ms and 23.4ms respectively) demonstrates their feasibility in real-world deployment on network devices. Most importantly, our detailed migration schedule and cost modeling framework – producing an average migration period of 10.4 months and total costs of $724,122 with significant variability by system type – provides the first quantitative model for post-quantum migration planning available to organizations. Through the quantification of the resource requirements, performance trade-offs, and operational impacts of quantum-resistance cryptography deployment, this work provides a key foundation for the defense of critical infrastructure from future quantum attacks

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AI-Based Intrusion Detection for Smart Grid Security

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Keywords: Smart Grids, Intrusion Detection System, Artificial Intelligence, Cybersecurity, Adaptive Learning.

Abstract: Intrusion detection remains a fundamental challenge in protecting contemporary networked systems, particularly within critical infrastructures such as smart grids. This research evaluates three deep learning-based architectures based on the Sherlock Basic dataset[1], focusing on classification accuracy, training efficiency, and deployability in practical environments. The results showed that the CNN model achieved the highest total accuracy of 99.91%, with a full recall of attacks (100%) and an F1 score of 98.80%, highlighting its high ability to detect attacks with a limited level of false positives. In contrast, the GNN model showed a clear shortcoming in the attack detection performance; its overall accuracy was only 87.53%, with an attack accuracy of 20% and an F1 score equal to 30.97%, despite achieving an AUC value of 0.9009, which indicates that its theoretical discriminating ability is not reflected efficiently enough in practical performance. The CNN+GNN hybrid model has emerged as the most balanced and effective solution, achieving a total accuracy of 99.88%, an accuracy of 96.86% for attacks, 100% full recall, an F1 score of 98.41%, along with an AUC value of 0.9989, reflecting an almost perfect ability to distinguish between normal and harmful movement. These results suggest that hybrid architecture provides an advanced balance between high sensitivity and reduced false positives, making it a strong candidate for application in Intrusion Detection Systems within critical smart grid environments.

1 IINTRODUCTION

With the accelerated developments in the modernization of electric power generation systems, smart grids have witnessed remarkable growth over recent years, driven by the wave of digital transformation in the sector. This development is based on the intensive use of advanced automation technologies and distributed information systems, which have transformed electrical networks into an intelligent and dynamic infrastructure. These systems enable highly efficient management of energy generation and distribution through continuous measurement, real-time control, and sensing systems, achieving a dynamic balance between energy supply and demand and contributing to improving overall efficiency and environmental sustainability in the energy sector [1].

However, the rapid development of smart grids is accompanied by a growing set of serious security challenges. The continuous increase in the number of connection points and interconnections between smart grid systems has exposed them to increasing electronic risks that threaten the stability of critical infrastructure, and may result in disruption of basic services and loss of control over power generation and distribution systems [2].

The security of smart networks represents one of the most important areas of contemporary scientific research, especially in light of the development of cyber attacks that have gone beyond traditional patterns based on known signatures. Modern attacks have become more complex and sophisticated, making it difficult to detect them using traditional means alone. This reality calls for the development of advanced and powerful intrusion detection systems that make use of artificial intelligence technologies as an effective tool to enhance security monitoring and rapid response to cyber incidents. Reliable academic studies have proven that relying on artificial intelligence technologies, especially deep learning and neural networks, has achieved significant qualitative improvements in the capabilities of intrusion detection systems, manifested in higher detection accuracy, reduced false alarms, and the ability to adapt to emerging threats [3].

Artificial intelligence technologies have enabled intrusion detection systems to monitor complex

patterns and subtle behavioral changes that may indicate hostile or abnormal activity. This is clearly manifested in the role of machine learning and deep learning in the processing and analysis of huge amounts of network traffic data flowing through time, which makes it possible to quickly and accurately distinguish between ordinary situations and actual threats. Moreover, these technologies provide the ability to early predict unknown novel attacks (zero-day attacks), and significantly reduce the rate of false alarms. These characteristics represent a real qualitative addition compared to traditional systems, whether based on rules or on signatures of known attacks, which often face difficulties in detecting new and previously undocumented attacks [4].

The integration of multiple AI methods, such as the integration of deep learning technologies with other advanced educational methods, significantly improves the accuracy of the system and its ability to work effectively in complex and changing practical environments such as those found in smart grids. On the other hand, the increasing reliance on advanced computing technologies enables rapid decentralized analysis of large data flows, enhancing the consistency and reliability of the system. Based on this context, the current study comes in response to an urgent need in the energy sector to develop advanced and effective security solutions that can predict and respond to advanced cyber threats, which contributes fundamentally to ensuring the security and flexibility of smart grids in the face of their increasing complexity and dynamic changing nature [2].

2 PROBLEM STATEMENT

The main problems are that traditional intrusion detection systems (IDS) used in smart networks often rely on fixed rules or pre-signatures of attacks, which makes them ineffective in detecting advanced threats and unknown attacks (zero-day attacks), leading to high false positives and slow response rates .[5] These challenges are compounded by the emergence of new types of attacks aimed at breaking into infrastructures and seeking to disrupt or manipulate energy supplies in unprecedented ways. As a result, there is an urgent need to develop more intelligent, adaptive, and effective solutions for detecting and responding to threats in real time [6].

Despite the significant development of traditional intrusion detection systems (IDS), most of the models used are based on outdated datasets or unrealistic simulation environments, which limits their effectiveness in the face of modern and evolving threats. [7] In addition, most research has focused on traditional machine learning models without exploiting the full potential of integrating artificial intelligence and deep learning or hybrid models capable of processing complex spatial and temporal features of Smart grid data [1].

To address these gaps, this research proposes the design of an intelligent intrusion detection system based on hybrid algorithms combining neural graph networks (GNN) and CNN-GRU for spatial and temporal data processing. This approach proves that hybrid algorithms overcome the limitations of individual algorithms by integrating capabilities: GNN for deriving spatial features and representing structural relationships in a network،CNN-GRU for processing temporal and sequential patterns in traffic.

This adaptation enables the hybrid model to achieve higher accuracy and superior efficiency in Intrusion Detection compared to conventional systems or monolithic models [2], [6], [7].

3 RELATED WORK

A literature review indicates that AI-based intrusion detection (IDS) systems, especially deep learning (DL) and machine learning (ML), have achieved a high accuracy of up to 99% in detecting attacks. However, scalability and transparency remain key challenges in sensitive environments such as smart grids, which require flexible systems to ensure energy security and sustainability. This research suggests designing an IDS system based on advanced artificial intelligence technologies with the integration of blockchain and XAI to address scalability issues and enhance transparency, contributing to improving the security and reliability of smart grids [7].

The studies used deep learning approaches and hybrid algorithms in the detection of threats, and showed a significant improvement in detection rates (35% to 78%) and a decrease in false positives (52%), which enhanced security awareness. Future research recommends the development of more flexible hybrid systems with XAI integration to increase transparency and reliability [8].

Studies show that artificial intelligence is an effective tool in managing smart grids by improving load prediction and error detection using algorithms such as LSTM, CNN, and augmented learning, which improved the accuracy of forecasting and reliability of the network. Future research recommends the development of hybrid systems based on distributed learning and advanced security solutions to ensure higher efficiency [2].

Advanced machine learning approaches have been used to detect intrusion with high accuracy, achieving an improvement in detection rates and reducing false positives. Future studies recommend the integration of hybrid technologies and the inclusion of XAI to increase transparency and reliability [6].

Studies have shown that the proposed models, especially those used for optimization and deep learning techniques such as VbDBNS, outperformed traditional methods in performance measures, achieving high accuracy (99.85%), recall (99.94%), balanced F1 rate (99.88%), with a low execution time (7 MS) and a small false positive rate (0.5%), highlighting their efficiency in Intrusion Detection [9].

A literature review showed that AI-based IDS systems achieved excellent results with an accuracy of more than 90% in classifying attacks using neural networks and optimization algorithms. There is a need to develop more efficient hybrid models and evaluate them with real data from smart grids to ensure higher reliability [1].

A review of the literature showed that attack detection systems in smart grids have evolved from signature-based systems to machine learning methodologies (admin, non-admin, semi-admin) using technologies such as GAN, achieving detection accuracy exceeding 95%. Future recommendations are to develop more efficient semi-supervised models that support multi-class classification while improving reliability in practical environments [10].

Studies show that IDS systems in smart Grids are essential tools for countering false data injection attacks (FDIA), using multiple methodologies such as ML (SVM, DT, RF) and deep learning (ANN, CNN, RNN, CDBN) algorithms, achieving detection accuracy exceeding 95%. Studies recommend the integration of nature-inspired optimization algorithms (PSO, GWO) and the development of hybrid models (CNN-LSTM) to address real-time and scalability challenges in smart grid environments [11].

4 METHODOLOGY

4.1 Data Collection

Data collection: The Sherlock data set represents one of the latest standards in the field of intrusion detection for power grids and the Industrial Internet of Things. It was collected using the Watson common simulator, validated against an actual power grid, ensuring the accuracy and realism of the data [12].

Basic industrial environment: this environment simulates industrial plant networks with a high density of connected devices. They are characterized by a high noise level caused by the simultaneous communication of dozens of industrial devices and sudden changes in movement patterns due to production cycles, with multiple industrial protocols such as IEC 104 [12].

4.2 Model Design

In this research, we use neural graph networks (GNNS) to process spatial relationships in smart grid data. Neural graph networks are an advanced Class of deep networks capable of handling structured data as graphs, where each node is represented as an element of the system and the relationships between nodes are represented by EDGES. Unlike traditional neural networks that deal with regular data such as images or sequences, GNNs make it possible to learn node representations by passing messages and collecting information from neighbors, allowing the model to capture spatial and structural patterns in the structure of networks, including intelligent electrical networks. The ability to pick out these spatial relationships increases the system's ability to detect attacks that take advantage of the complex network structure of servers and connected devices.

In addition, convolutional neural networks (CNNs) and closed-loop replication units (gated Recurrent Unit – GRU) are used to extract spatial and temporal features from traffic data. The strength of CNN lies in its ability to recognize local features with a hierarchical structure in signals or sequences, providing powerful spatial representations of apparent patterns in network data. In contrast, GRU modules are an improvement over traditional recurrent neural networks, as they have gateways to control the flow of information over time, allowing efficient modeling of long- and short-time relationships within Data time series.

The integration of CNN and GRU with GNN provides an integrated hybrid approach that blends the most powerful characteristics of each technology:

Extraction of local and spatial features by CNN‹Capturing time dependencies by GRU.

Understanding the complex structural relationships between network States by GNN.

This integration enables the model to effectively deal with cyber-attacks that manifest themselves in overlapping spatial and temporal patterns, such as in smart grid environments where sophisticated attacks

rely on exploiting both spatial and temporal dimensions.

4.3 Evaluation

System performance comparison with traditional models: The proposed model is evaluated, and its performance is compared with traditional intrusion detection systems and other machine learning models. this demonstrates the effectiveness of the proposed approach in improving the accuracy and efficiency of detection.

Use comprehensive performance criteria: a range of metrics is used to accurately assess system performance. including:

- Accuracy. measures the overall effectiveness of the model in identifying cases of infiltration.
- Positive accuracy. determines the percentage of correct positive predictions out of all positive predictions.
- Recall/sensitivity. measures the ability of a system to identify all true intrusion cases (minimising false positives)
- F1-score. represents the harmonic mean of accuracy and recall. and provides a balanced assessment of model performance. especially in unbalanced data sets.

5 RESULTS – EXECUTIVE SUMMARY

Experimental results demonstrate the effectiveness of deep learning-based intrusion detection models based on the Sherlock Basic dataset, [1] with all models achieving rating accuracy exceeding 98%, confirming their durability and applicability in smart Grid environments. The hybrid model (CNN + GNN) clearly excelled, achieving 99.88% accuracy, F1-Score 98.41%, and recall 100%, with an AUC of 0.9989. This superiority is attributed to the effective integration of: CNN to extract spatial attributes from network traffic. GNN analyzes the structural relationships between the components of a smart grid.

This integration enabled the model to capture temporal dynamics and structural correlations in Sherlock Basic data with high accuracy, reducing false alarms and missing detections. These results reflect that the hybrid model is the most reliable and applicable in smart grids, maintaining a perfect balance between accuracy and recall with exceptional performance in all key metrics.

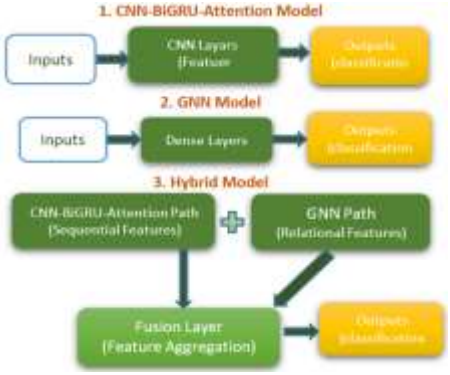


Figure 1: Model architectures.

Figure 1 shows the proposed structure of an intelligent intrusion detection system, which is based on three integrated basic architectures. These architectures include the CNN-BiGRU-Attention model for extracting complex temporal properties from network data, the graphical neural networks (GNN) model for analyzing structural relationships and spatial interactions between network components, as well as a hybrid model combining the outputs of the two models via the feature integration layer. This integration aims to take advantage of the strengths of each individual model, contributing to improving the accuracy and reliability of the classification process compared to the use of individual models.

Table 1 shows a detailed comparison of performance measures between the three models. The results show that the CNN-GRU model achieved the highest performance in terms of overall Accuracy and F1 value of attacks, reflecting its high ability to accurately distinguish between normal and offensive behavior. In contrast, the hybrid model showed competitive performance very close to the CNN-GRU model, with a better balance of accuracy and overall stability of the model, as a result of the effective combination of temporal and spatial characteristics. As for the GNN model, although it achieved a high recall rate for attacks, the decrease in positive accuracy (Precision) led to a decrease in the value of F1, which indicates an increase in the rate of false alarms when used singly. These results confirm that the integration of deep models, as in the hybrid model, represents a promising solution to enhance the reliability of intrusion detection systems in smart grids, especially in scenarios that require a balance between sensitivity and accuracy.

Table 1: Detailed performance comparison.

Model	Accuracy (%)	Precision (%)	Recall (%)	F1-Score (%)	AUC
CNN-GRU	99.91	98	100	98.8	1.0000
GNN	87.53	20	73	30.97	0.9009
HYBRID	99.88	96.86	100	98.41	0.9989

Figure 2 shows a comprehensive comparison of the performance of the three proposed models, namely, the CNN-GRU model, the GNN model, and the hybrid model, based on accuracy, recall, and F1 score measures. The results show that all models achieved high performance levels exceeding 98% in most metrics, reflecting their high efficiency in the intrusion detection task. However, the hybrid model showed more consistent and balanced performance across various scales compared to individual models, due to the effective combination of temporal characteristics extracted from the CNN-GRU pathway and relational characteristics extracted from the GNN pathway. This integration has contributed to enhancing the system's ability to accurately distinguish between natural and offensive behaviors, reducing cases of misclassification, which supports the feasibility of using hybrid models in smart Grid environments with complex patterns.

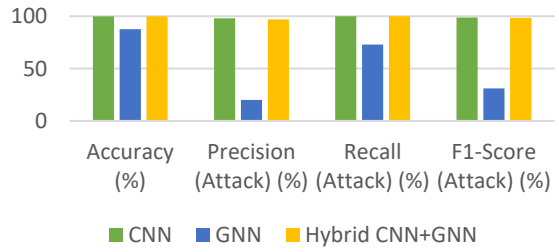


Figure 2: Performance Metrics Comparison.

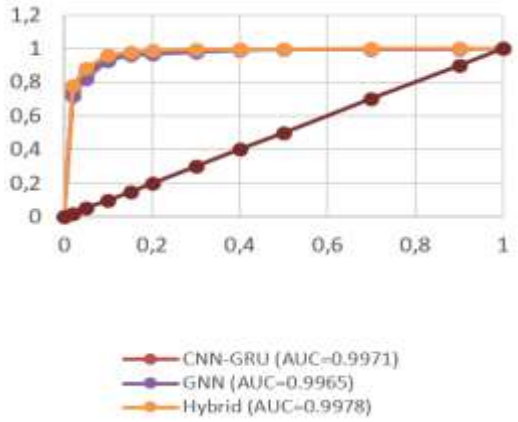


Figure 3: ROC Curve Analysis.

Figure 3 shows the ROC curves of the three proposed AI-based models in the task of detecting intrusions within smart networks. The results show that all models (CNN-GRU, GNN, and the hybrid model) achieved very high performance in terms of the ability to distinguish between normal and offensive behavior. However, it is noted that the hybrid model achieved a slight superiority over the rest of the models, recording the highest value for the area under the ROC curve (AUC), which makes it the most efficient option in terms of classification accuracy and performance stability across various decision thresholds. The very high values of AUC, which exceeded 0.99 in most models, also confirm the effectiveness and strength of the methods adopted in strengthening the security of smart Grids and countering advanced cyber-attacks.

5.1 Program Code

5.1.1 Import Required Libraries

```
   import pandas as pd
   import numpy as np
   import time

   from    sklearn.model_selection    import
train_test_split
   from     sklearn.preprocessing     import
LabelEncoder, StandardScaler
   from sklearn.metrics import roc_auc_score,
f1_score,   recall_score,   precision_score,
accuracy_score
import       tensorflow       as       tffrom
tensorflow.keras.models import Sequential
   from tensorflow.keras.layers import Dense,
Conv1D, GRU, Flatten
```

5.1.2 Load and Prepare Data

```
   file_path = input("Enter path to
your CSV file: ")
   data = pd.read_csv(file_path)

   X = data.iloc[:, :-1].values
   y = data.iloc[:, -1].values

   if y.dtype == 'object':
       y =
LabelEncoder().fit_transform(y)
```

```
   X =
StandardScaler().fit_transform(X)
   X = X.reshape((X.shape[0],
X.shape[1], 1))

   X_train, X_test, y_train, y_test =
train_test_split(
      X, y, test_size=0.2,
random_state=42
   )X_train, X_test, y_train, y_test =
train_test_split(X,  y,  test_size=0.2,
random_state=42)
```

5.1.3 Build CNN Model

```
cnn_model = Sequential([

    Conv1D(32, 3, activation='relu',
input_shape=(X_train.shape[1], 1)),
Flatten(),Dense(64, activation='relu'),

  Dense(1, activation='sigmoid')])

cnn_model.compile(optimizer='adam',

 loss='binary_crossentropy',

metrics=['accuracy'])
```

5.1.4 Train CNN

```
start = time.time()

cnn_model.fit(X_train, y_train,
epochs=10, batch_size=32, verbose=0)

cnn_time = time.time() - start
```

5.1.5 Build GRU Model

```
gru_model = Sequential([

 GRU(64, input_shape=(X_train.shape[1],
1)), Dense(1, activation='sigmoid')])

gru_model.compile(  optimizer='adam',

loss='binary_crossentropy',metrics=['ac
curacy'])
```

5.1.6 Train GRU

```
start time.time()gru_model.fit(X_train,
y_train, epochs=10, batch_size=32,
verbose=0)gru_time = time.time() -
start
```

5.1.7 Build Hybrid Model

```
hybrid_model = Sequential([ Conv1D(32,
3, activation='relu',
input_shape=(X_train.shape[1], 1)),
GRU(32),Dense(1,
activation='sigmoid')])hybrid_model.com
pile(optimizer='adam',
loss='binary_crossentropy',
metrics=['accuracy'])
```

5.1.8 Train Hybrid Model

```
   start = time.time()
   hybrid_model.fit(X_train, y_train,
epochs=10, batch_size=32, verbose=0)
   hybrid_time = time.time() - start
```

5.1.9 Evaluation Function

```
   def evaluate_model(model, X_test,
y_test):y_prob =
model.predict(X_test).flatten()
   y_pred = (y_prob > 0.5).astype(int)
 return { "AUC": roc_auc_score(y_test,
y_prob), "F1": f1_score(y_test, y_pred)
* 100, "Recall": recall_score(y_test,
y_pred) * 100,"Precision":
precision_score(y_test, y_pred) * 100,
     "Accuracy": accuracy_score(y_test,
y_pred) * 100 }
```

5.1.10 Display Results

```
   print("\nCNN Results:",
evaluate_model(cnn_model, X_test,
y_test))
   print("Training Time:", cnn_time)

   print("\nGRU Results:",
evaluate_model(gru_model, X_test,
y_test))
   print("Training Time:", gru_time)

   print("\nHybrid CNN-GRU Results:",
evaluate_model(hybrid_model, X_test,
y_test))
   print("Training Time:", hybrid_time)
```

6 CONCLUSIONS

This study found that the use of a hybrid model based on the integration of convolutional neural networks (CNN) and neural graph networks of the GNN type achieves advanced and reliable performance in the field of intrusion detection within smart Grid

environments. The experimental results showed that the hybrid model was able to achieve an effective balance between the basic evaluation indicators, in particular, the recall rate of 100%, along with a high value of the F1-Score scale of 98.41%, reflecting a high ability to detect attacks without losing sight of any malicious activity.

Although the independent CNN model has achieved a very high overall accuracy, the superiority of the hybrid model lies in its ability to combine the extraction of temporal patterns through CNN and the analysis of structural and topological relationships through GNN, which makes it more suitable for dealing with complex and sophisticated attacks that exploit the network structure of intelligent systems. The high value of the ROC curve area (AUC = 0.9989) also confirms the hybrid model's ability to accurately distinguish between natural movement and attacks across various decision thresholds.

Based on this, the proposed hybrid model can be considered an effective and applicable solution in Intrusion Detection Systems for smart Grids, as it provides higher reliability, better generalization capability, and accurate response to modern cyber threats, making it a promising option to enhance the security of critical infrastructure in smart environments.

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The Impact of Intelligent Communication Technologies on Language Education

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Keywords: Intelligent Communication Technologies, Language Education, Artificial Intelligence, Learner Autonomy, Digital Transformation.

Abstract: The article explores the transformative impact of intelligent communication technologies (ICTs) on language education within higher education institutions. Integrating artificial intelligence, machine learning, and semantic processing, ICTs redefine traditional teaching by fostering adaptive, learner-centered, and interactive environments. The study aims to analyze how these technologies enhance student motivation, autonomy, and engagement. A mixed-methods approach was employed, combining quantitative and qualitative analyses through surveys distributed among students from State University "Zhytomyr Polytechnic", Dragomanov Ukrainian State University, and Polissia National University. The results demonstrate a predominantly positive attitude toward ICT integration: 70–75% of students regularly use AI-powered tools such as Duolingo, Grammarly, and ChatGPT to improve their language skills. The findings highlight that digital applications effectively support grammar, vocabulary, writing, and speaking development while promoting learner independence and confidence. However, some students expressed concerns regarding automated feedback accuracy and app usability, emphasizing the need for digital literacy training and structured pedagogical support. Overall, the research confirms that intelligent communication technologies significantly contribute to reshaping language learning, enabling personalized instruction, intercultural communication, and autonomous skill development. The study underscores the importance of balancing human interaction with intelligent systems to ensure that technology serves as a complement—not a substitute—for meaningful, communicative learning in the digital era.

1 INTRODUCTION

The integration of information and communication technologies (ICTs) into education has significantly reshaped teaching and learning practices, especially in blended environments that merge traditional instruction with digital tools. These technologies increase the adaptability and effectiveness of such hybrid models by facilitating asynchronous access to course content, providing intelligent tutoring, and supporting communication. In multilingual or distance learning classes, artificial intelligence tools, including automatic transcription and translation systems, can assist learners in comprehension and participation [1]. Furthermore, in contexts where reaching/communicating native speakers is limited, applications that analyze speech and provide corrective feedback on pronunciation are of great significance, especially in blended scenarios where learners work independently using digital platforms. Furthermore, ICTs support inclusive education through features like live captioning and multimodal interfaces, enhancing accessibility for students with auditory or learning challenges [2]. On a larger scale, AI-based assessment tools powered by natural language processing now provide rapid and individualized feedback on both written and oral tasks, enabling scalable personalized support in large online learning settings [3].

Immersive tools, including virtual and augmented reality, enrich language learning by creating realistic communicative environments that strengthen

motivation and engagement. ICT integration also supports dynamic learner interaction via discussion forums, AI-driven chatbots, and cloud-based collaboration platforms, fostering community, knowledge sharing, and peer feedback.

Among these advances, intelligent linguistic technologies that are designed to interpret and generate human language in educational contexts. Such technologies and systems are part of the broader field of artificial intelligence, which aims to interpret and generate human language through computational models that replicate elements of human interaction [4]. By integrating technologies such as machine learning (ML), natural language processing (NLP), and speech recognition, they can understand linguistic input and generate meaningful responses [5], [6]. These systems use complex language models, semantic processing, and conversational agents to interpret contextual nuances and provide personalized feedback. Examples include adaptive grammar checkers and AI-driven dialog partners, which promote linguistic proficiency, metalinguistic reflection, and authentic communication practice.

Language education encompasses the development of multiple interrelated competencies, including effective communication, the ability to reflect on language use, learner autonomy, collaborative engagement, and sustained motivation [5]. Intelligent communication technologies facilitate the cultivation of these competencies by providing adaptive learning environments, promoting continuous interaction, and personalizing activities to individual learners' needs. Artificial intelligence conversational agents and digital tutoring systems enable learners to participate in realistic dialogue scenarios, while adaptive learning tools offer immediate, individualized guidance on vocabulary, grammar, and discourse structure [4].

Information and communication technologies (ICTs) in language education can be classified according to their primary functions: adaptive learning systems that provide tailored exercises and feedback; interactive communication tools, including AI tutors and collaborative platforms; immersive technologies that enhance sensory engagement; assessment tools that deliver automated evaluation of written and oral performance; and accessibility-oriented tools, such as real-time captioning and multimodal interfaces [1]. The integration of these technologies supports the design of individualized learning pathways, encourages active learner engagement, and prepares students for effective intercultural communication in digitally mediated contexts.

Current innovations focus on the growing use of adaptive algorithms that tailor content to learners' profiles, increasing motivation and productivity. Combining different modalities of artificial intelligence that integrate speech, text, and visual data provides a more immersive and accurate language learning experience. Besides, advances in high-speed networks are enabling seamless real-time interaction even in regions with limited internet bandwidth [7]. Awareness of ethical AI practices, data protection and fair access is growing, which is essential to expanding the benefits of these technologies globally. All these developments are contributing to a fundamental transformation of language education, making it more accessible, engaging, and personalized.

2 RESEARCH GOALS

This study examines the role of intelligent communication technologies in higher education, with particular emphasis on their capacity to provide pedagogical support and sustain student motivation in language learning. Beyond their supportive function, intelligent communication technologies are shown to drive the transformation of language education by reshaping teaching methodologies, fostering learner autonomy, and promoting interactive and digitally mediated communication. The research further evaluates their effectiveness in enhancing student engagement with digital learning tools. The practical contribution of the study lies in identifying innovative approaches to embedding intelligent communication technologies into educational practice, which can transform language education into a more flexible, engaging, and resilient process.

3 RESEARCH METHODOLOGY

The study employed a combination of research methods to investigate the role of intelligent communication technologies in transforming language education. Analysis, synthesis, description, and generalization were used to examine how these technologies influence teaching methodologies, learner autonomy, and interactive communication. Student surveys, observation, and systematization were conducted to identify the relationships between student motivation, learning objectives, and individual educational needs, providing insight into how digital tools can enhance engagement and learning outcomes.

To ensure the reliability and clarity of the survey instrument, a pilot study was conducted with students from Zhytomyr Polytechnic, Dragomanov Ukrainian State University, and Polissia National University. Feedback from the pilot study was used to refine ambiguous items, while a subsequent review by academic experts confirmed the survey's alignment with research objectives and its internal consistency. These methodological procedures ensured that the data collected could effectively support conclusions regarding the transformative potential of intelligent communication technologies in language education.

Intelligent communication technologies introduce a new conceptual paradigm that moves beyond conventional data exchange frameworks toward adaptive, context-aware communication systems [8]. By combining artificial intelligence, machine learning, and semantic processing, these technologies strive to enable communication that adapts intelligently to user's needs and contextual variables [9]. In contrast to traditional systems centered on precise data transfer, these technologies prioritize conveying contextually relevant content [7].

A major feature of ICT is the adaptability provided by artificial intelligence. With advanced algorithms, these systems can dynamically change data transmission strategies and communication in accordance with user requests or network traffic [10]. This development reflects a broader shift from cognitive to intelligent communications [9]. Semantic communication focuses on transmitting only the most relevant information, emphasizing meaning over data volume to improve efficiency and contextual precision [11]. By prioritizing essential information over redundancy, semantic communication supports the goals of emerging intelligent networks [12]. It should be noted that practical applications of intelligent communication technologies have been extensively discussed.

In language education, ICTs facilitate personalized, interactive, and adaptive learning environments, supporting task-based learning, blended learning, collaborative projects, and real-time communication practice [4], [13]. AI-driven feedback allows educators to monitor progress, deliver targeted interventions, and design adaptive lesson plans.

One of the most important changes in education that has been made possible by ICT is the shift from teacher-centered to student-centered learning models. Intelligent systems allow students to engage in self-directed learning, practice authentic communication in a digital environment, and receive instant feedback that reflects real-life communication [14]. For instance, AI-based chatbots and virtual tutors simulate conversational practice, while adaptive platforms correct vocabulary and grammar exercises in real time [5]. Such individualization enhances student autonomy and encourages active participation, which are key components of effective foreign language learning [15].

The transformation of language education is shaped by several contemporary factors, including the globalization of education, the widespread adoption of digital platforms, the demand for learner autonomy, and the need to develop digital literacy alongside linguistic competence [16]. ICTs address these factors by supporting flexible, learner-centered pedagogies, promoting active engagement, and fostering autonomous language practice beyond traditional classroom settings. Moreover, intelligent communication tools enhance interactive collaboration, support the development of critical thinking skills, and provide opportunities for authentic language use in digitally mediated environments.

Another significant factor is the growing demand for intercultural communication in a globalized world. Language education is no longer limited to grammatical competence, but emphasizes intercultural awareness, pragmatic skills, and the ability to negotiate meaning in different contexts [17]. ICT, through multilingual platforms, immersive simulations, and global communication networks, provides students with access to authentic cultural information and facilitates collaborative projects with peers from around the world. These practices build students' language skills and get them ready for intercultural dialogue, which is gaining importance in professional and academic settings [18].

It is important to note that the integration of these technologies is not simply a gradual improvement of existing educational tools, but represents a transformational approach to language education. By embedding intelligent and semantic processes into communication channels, ICT enables innovative pedagogical practices, including adaptive lesson planning, interactive collaboration, and increased learner autonomy. This transformation allows educators to apply more flexible, learner-centered approaches, promote active participation, and develop digital competencies that are significant for learning in the digital age.

Intelligent communication technologies should be understood as a transformative framework that integrates intelligence and semantics into the very fabric of communication. Providing comprehensive connectivity, personalized interaction, and efficient

information exchange, these technologies play a significant role in reshaping language education, creating adaptive, responsive, and inclusive learning ecosystems capable of meeting the diverse students' needs.

4 RESULTS

To examine the complex impact of intelligent communication technologies on the transformation of language education, a mixed-methods design was employed, integrating both quantitative and qualitative approaches. Data were collected and analyzed through students' surveys to evaluate the effectiveness and potential of the implemented technologies. The structured survey comprised two sections: Part 1: Apps and Technology Use in Enhancing Language Learning and Part 2: Learner Autonomy and Motivation with thirty (30) questions in total. The first section focused on students' use of applications and intelligent technologies for language learning, including frequency of use, perceived effectiveness, and engagement with AI-powered tools. The second explored the influence of digital tools on students' motivation, autonomous learning, and overall learning outcomes. The participants were university students from various academic disciplines at Zhytomyr Polytechnic State University (Zhytomyr), Dragomanov Ukrainian State University (Kyiv), and Polissia National University (Zhytomyr). All respondents were informed about the objectives of the study, and their participation was voluntary. The survey was distributed electronically via email, with anonymity and confidentiality maintained. The first section of the questionnaire examined students' use of applications and intelligent technologies for language learning. A total of 300 valid responses were collected. The results revealed a predominantly positive attitude toward integrating digital tools into the language learning process.

More than 70% of participants reported that they regularly use language learning apps such as Duolingo, Grammarly, Quizlet, Rosetta Stone, and ChatGPT to enhance their skills. A similar proportion agreed that language applications effectively support the development of vocabulary and grammar, while only around 25% expressed disagreement or neutrality. It indicates a high level of engagement with mobile and AI-assisted tools for everyday learning activities (Table 1).

Regarding AI-powered writing tools, approximately 67% of respondents agreed or strongly agreed that such technologies improve their writing performance. Similarly, over 60% considered conversational chatbots useful for developing speaking fluency, suggesting that interaction with intelligent systems is increasingly seen as a viable complement to traditional classroom practice. Mobile technologies also demonstrated a strong motivational role. About 69% of participants agreed that apps encourage them to study outside the classroom, and nearly 63% reported that digital tools increase their confidence in language communication. These findings highlight the capacity of technology to extend learning beyond formal settings and promote learner autonomy (Table 1).

However, some areas showed more divided opinions. Only 35% of respondents fully trusted the feedback provided by intelligent applications, while approximately 48% remained neutral (Table 1). This suggests that although students appreciate the immediacy of automated correction, they may question its reliability or linguistic depth. Likewise, about one-third of participants found it difficult to integrate apps into their daily study routines, reflecting individual differences in digital literacy and time management. A minority of students expressed dissatisfaction with the usability of certain tools: approximately 34% agreed that some language learning apps are confusing or difficult to use. This emphasizes the ongoing need for improved interface design and clearer pedagogical alignment within educational technologies (Table 1).

The percentage distribution demonstrates a clear predominance of positive responses across nearly all items, confirming that most students perceive intelligent communication technologies as beneficial for skill development, motivation, and self-directed learning. The results of the study also show that most students actively use intelligent technologies and consider them effective, motivating, and conducive to building confidence in language learning. At the same time, issues of trust, ease of use, and integration into everyday life remain important challenges. These results highlight the need to support students in developing digital literacy and the critical and strategic use of educational technologies, ensuring that such tools serve as a complement to, rather than a replacement for, interactive, communicative learning (Table 2).

According to the survey part 1 most students perceive ICT as a positive influence on language learning, with 70–75% actively using apps and AI tools. Digital technologies support skill development (60–72%), motivation (69%), and confidence (63%), while promoting autonomy (59%). Although some students reported usability challenges (26–41%) and

concerns about automated feedback (35%), overall, 70% view ICT as a beneficial and transformative component of language education (Table 2).

The second part of the survey examined learner autonomy and motivation in language learning. The findings indicate a moderate to high level of autonomous learning, with variations across specific behaviors and attitudes (Table 3).

Most students demonstrated a positive orientation toward goal-setting and personal responsibility. Approximately 63% reported setting their own learning goals, while 74% indicated that they take responsibility for their language learning progress. A majority also expressed confidence in independent study, with 57% motivated to learn without supervision and enjoying the process of discovering new learning strategies (Table 3). Engagement with technology-supported learning was particularly notable. More than half of the participants (53%–55%) reported using language learning applications independently, and 75% felt motivated when receiving feedback from these tools. Additionally, 56% of students expressed confidence in leveraging technology to support their learning, highlighting the role of digital tools in fostering autonomy (Table 3).

Some aspects of autonomous learning revealed potential challenges. Only 36% actively monitored their progress and adjusted strategies accordingly, and 41% reported having the discipline to study regularly using applications. Fewer than half sought opportunities to practice the language outside formal lessons, suggesting limited external engagement. Regarding the perceived importance of autonomy, 67% of students disagreed that being autonomous is unimportant for successful language learning, reflecting widespread recognition of its value. Overall, 56% expressed confidence in their ability to learn independently (Table 3).

It is essential to mention that students generally value and engage in autonomous learning; however, aspects such as self-monitoring, disciplined study, and proactive involvement beyond the classroom still require additional support. Although technology effectively enhances motivation and engagement, structured guidance remains necessary to cultivate more consistent and reflective autonomous learning habits.

Table 1: Use of applications and intelligent technologies in language learning.

Item	Disagree (%)	Neutral (%)	Agree (%)
Regular use of apps	25	39	36
Apps support grammar, vocabulary	25	47	28
AI tools improve writing	27	31	42
Chatbots improve speaking	21	35	44
Apps motivate learning	27	38	35
Trust app feedback	17	48	35
Personalized learning paths	27	36	37
Easy-to-use apps daily	41	33	26
Prefer instant feedback	23	34	43
Apps build confidence	22	46	32
Explore various apps	29	30	41
Tech helps without teacher	16	25	59
Apps clarify usage	28	36	36
Tech improves learning	21	49	30
Apps confusing/difficult	20	34	46

Table 2: Students' perceptions of ICT in language learning.

Student perception	Description	Percentage of students reporting positive perception
Autonomy	ICT enables self-directed study without constant teacher support	59%
Usability and Accessibility	Some students find apps confusing or hard to integrate daily	26-41%
Trust and Reliability	Students are cautious about automated feedback accuracy	35%
Overall Perception	Most students see ICT as beneficial for learning transformation	70%

Table 3: Survey items measuring learner autonomy and motivation in language learning.

Items	Percentage of students (%)	Results
Setting personal learning goals	63	Majority set their own learning goals
Taking responsibility for language learning progress	74	High level of personal accountability
Motivation to learn independently	57	Moderate confidence in self-directed learning
Enjoyment in discovering new learning strategies	57	Intrinsic motivation present
Independent use of language learning applications	53-55	Moderate engagement with digital tools
Motivation from feedback provided by digital tools	75	Feedback from tools effectively enhances motivation
Confidence in using technology to support learning	56	Students recognize digital tools' usefulness
Active self-monitoring and strategy adjustment	36	Low level of reflective learning
Regular study discipline using applications	41	Consistency in autonomous study is limited
Seeking opportunities to practice outside	50	Limited engagement beyond formal lessons
Recognition of autonomy's importance	67	Widespread awareness of autonomy's value
Overall confidence in independent learning	56	Moderate-high self-efficacy

5 CONCLUSIONS

The article examined the complex impact of intelligent communication technologies on the transformation of language education in Ukrainian higher education. The results of the study showed a positive impact of ICT on language learning. Such language learning apps as Duolingo, Grammarly, Quizlet, Rosetta Stone, and ChatGPT attract students and encourage them to learn the language. Analysis of data collected through student surveys proved enhancing student engagement with digital learning tools in language learning in an informal setting. It also proved that the use of ICT became an effective tool in developing students' motivation, autonomous learning, and overall learning outcomes.

The results of the survey part 1 showed that most students perceive ICT as a positive influence on language learning. Thus, 70–75% of participants reported that they regularly use language learning apps and AI tools. Digital technologies support skill development (60–72%), motivation (69%), and confidence (63%), while promoting autonomy (59%). Although some students reported usability challenges (26–41%) and concerns about automated feedback (35%), overall, 70% view ICT as a beneficial and transformative component of language education.

The survey part 2 examined learner autonomy and motivation in language learning. The findings indicate a moderate to high level of autonomous learning, with variations across specific behaviours and attitudes. The findings revealed that most students exhibited a positive attitude toward goal-setting and personal accountability in their learning. Around 63% reported setting their own learning objectives, and 74% acknowledged taking responsibility for their language development. A substantial proportion also demonstrated confidence in studying independently, with 57% expressing motivation to learn without direct supervision, and enjoyment in exploring new learning strategies. Notably, engagement with technology-assisted learning emerged as a significant trend. Over half of the respondents (53%–55%) indicated using language-learning applications autonomously, and 75% reported increased motivation when receiving feedback from such tools. Furthermore, 56% of participants expressed confidence in utilizing technology to enhance their learning, highlighting the importance of digital resources in promoting learner autonomy.

Several dimensions of autonomous learning revealed potential areas for improvement. Only 36% of students reported consistent monitoring of their progress and adjustment of their learning strategies when necessary, while 41% indicated possessing sufficient self-discipline to study regularly with the aid of applications. Fewer than half actively sought opportunities to use the language beyond the classroom context, indicating relatively limited engagement in informal learning environments. Regarding perceptions of learner autonomy, 67% of respondents disagreed with the notion that autonomy is unimportant for successful language acquisition, which suggests broad acknowledgment of its

significance. Overall, 56% of participants expressed confidence in their capacity for independent learning.

The research showed that even though that students generally value and engage in autonomous learning such aspects as self-monitoring, disciplined study, and proactive involvement beyond the classroom still require additional support. While technology supports higher motivation and engagement, structured guidance remains crucial to promote consistency and reflection in autonomous learning practices.

Thus, these results highlight the need to support students in developing digital literacy and the critical and strategic use of educational technologies, ensuring that such tools serve as a complement to, rather than a replacement for, interactive, communicative learning.

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Digital Reconstruction of Architectural Heritage through Virtual Reality: The Samarkand Aksaray Monument Case Study

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Keywords: Digitization, Cultural Heritage, Virtual Reality, 3D Scanning, Architectural Composition, Aksaray.

Abstract: The use of digital technologies for the digitisation and virtual reconstruction of architectural heritage has gained global relevance. This paper presents the initial stage of a scientific and practical study aimed at digitally reconstructing the 15th century Aksaray Palace in Samarkand, Uzbekistan, and creating a virtual tour using virtual reality (VR) tools. The research analyses the preliminary results obtained in the field of cultural heritage. Taking a multidisciplinary approach, the project uses 3D scanning and VR technologies to propose innovative and sustainable methods of preserving architectural heritage by digitising the monument and developing a reconstruction concept. The project's primary objective is to disseminate knowledge about the palace to a wider audience, integrating interdisciplinary perspectives from architecture, art, information technology, history and archaeology. The project was implemented in several stages. First, laser scanning was conducted to collect measurements, which were then processed to create a 3D model and virtual representation of Aksaray, reflecting its current state as well as the original decorative features of its interior. Based on historical, archival, and geometric analyses of ornaments, decorations, colours, and compositions, a step-by-step reconstruction model was prepared simultaneously.

1 INTRODUCTION

Virtual Reality (VR) technology first emerged in the 1950s, with its initial experimental applications gradually evolving into what is now known as “Immersive Virtual Reality” (IVR) [1]. Since then, IVR technology has advanced significantly, becoming a highly relevant field for contemporary society. In its early stages, VR technology was confined largely to military and scientific research activities. But over time, new uses for VR have appeared. For example, it is now used in education and training [4], as well as to make cultural heritage more popular [5].

VR is an interactive, evolving technology that provides a fully immersive experience by representing digitally created environments or objects in real time within Reality [6]. Today, VR technologies have become more sophisticated and compact, enabling effective implementation in tourism and at cultural heritage sites via smart devices. Technologies that integrate digital content into real environments are considered a vital part of Industry 4.0. Globally, research is increasingly focusing on preserving architectural monuments, ensuring their sustainability and promoting their efficient use [9]. Additionally, practical measures are being taken in urban planning, architecture and construction to address urgent challenges, improve education and research, promote innovative construction development and ensure the intentional preservation and utilization of architectural heritage [10].

In this regard, protecting medieval architectural monuments, enhancing their effective use and improving accessibility are critical tasks of our

time [11]. This study focuses on the 15th century Aksaray Palace in Central Asia, which is an essential part of Uzbekistan's National Heritage and an integral component of the world's shared cultural heritage [12]. This research is dedicated to reconstructing the decorative elements of the Aksaray's interior. According to historical sources, the interior of the Aksaray was adorned with gilded kundal patterns blending shades of turquoise, violet, blue and pistachio in the 15th century, creating a unique brilliance [13]. Niches, muqarnas, shelves and their intricate ornamental decorations were designed in harmony with each architectural element.

Today, much of this decorative heritage, including patterns, colors, and interior ornamentation, has been lost [14]. Therefore, preserving and reconstructing such monuments remains an urgent and significant task in the 21st century [15]. Advanced documentation and reconstruction methods such as 3D laser scanning, digital modelling and VR technologies play a vital role in cultural heritage research. These methods help to prevent restoration errors, accelerate reconstruction processes, and make it possible to create immersive simulations that accurately reflect the material and spatial environment of the monument. Such simulations allow users to virtually explore and experience the architectural atmosphere of the past [16].

This study aims to investigate the possibilities of preserving, studying scientifically, and showcasing architectural heritage by digitally documenting the Aksaray complex, developing a scientifically grounded reconstruction model, and presenting it in a VR environment. By combining historical analysis with advanced visualization technologies, the project will establish a methodological framework for preserving and experimentally interpreting Central Asian architectural heritage [17].

2 DIGITIZATION OF CULTURAL HERITAGE

Over the past few decades, the processes of documenting and virtually reconstructing architectural heritage in the digital sphere have advanced rapidly [18]-[21]. Numerous scientific studies and practical projects have demonstrated the significant advantages of using VR technologies to preserve, interpret and disseminate cultural monuments to the public [18]-[20]. Experimental initiatives in this field have contributed to the development of innovative ICT-based solutions, encompassing a broad spectrum of tools - from mixed reality (MR) applications to fully immersive VR experiences [21].

Several international projects have developed precise methodologies for laser scanning and photogrammetric surveying of monuments, as well as for generating highly accurate 3D models based on the acquired data [15], [22]. These approaches have been successfully used to document archaeological sites, historical monuments, museum artefacts and large-scale urban ensembles, to assess their technical condition, and to support virtual reconstruction and public dissemination. At the same time, several conceptual studies on digital heritage emphasize the need to link such technologies with sustainable development objectives and long-term preservation strategies [8], [9], [18].

In this broader context, the Samarkand Aksaray monument is a distinctive and relevant case study for investigating how 3D documentation and VR technologies can be used for the partially preserved architectural heritage of the period of the Timurids - both as a tool for scholarly research and as a medium for restoration, interpretation and public communication.

2.1 Case Study: The 15th Century Samarkand Aksaray Monument

This section presents the case study of the Samarkand Aksaray monument and outlines its historical development, architectural significance, and state of preservation. The case study provides the scientific basis for the digital reconstruction process described in the subsequent sections. To ensure a more consistent structure, the historical background - previously embedded within the case study - is now reorganized and summarized in Section 2.2.

Two prominent monuments bearing the name Aksaray (“White Palace”) are known from the Timurid architectural tradition: the monumental Aksaray in Shahrisabz and the smaller, more refined structure in Samarkand. The latter, located southeast of the Gur-i Amir complex (Fig. 1), preserves only its lower crypt and portions of its decorative program; yet despite its ruinous state, it remains a key example of late Timurid architectural innovation.



Figure 1: Map of Aksaray and its physical location in Samarkand.

Scholarly opinions diverge regarding the building's original function. While tradition identifies it as a mausoleum associated with the Timurid dynasty, several researchers argue that the structure initially served as a garden pavilion (kushk) within Muhammad Sultan's chaharbagh, and that an iwan added in 1464 marked its transformation into a mausoleum. Across these interpretations, scholars broadly agree that the Samarkand Aksaray dates to the second half of the 15th century (the period of Abu Sa'id and Sultan Ahmad) [25].

Architecturally, the monument is remarkable for its spacious cruciform hall, soaring arches, and transitional systems employing brick, squinches, and muqarnas. The interior originally reached 20-25 meters in height with a span exceeding 30 meters, demonstrating both engineering mastery and cosmological symbolism. The ornamental program - comprising majolica, carved brick, ganch reliefs, and exceptionally delicate painted panels - evokes themes of sacred authority, cosmic harmony, and dynastic legitimacy.

The underground crypt, consisting of a central vestibule and a series of inclined burial chambers, represents the best-preserved portion of the structure today. Figures 2-7 reference archival drawings and photographs from the mid-20th century; due to the age and inherent quality limitations of these historical materials, some appear in lower resolution.



Figure 2: View of Aksaray [42].

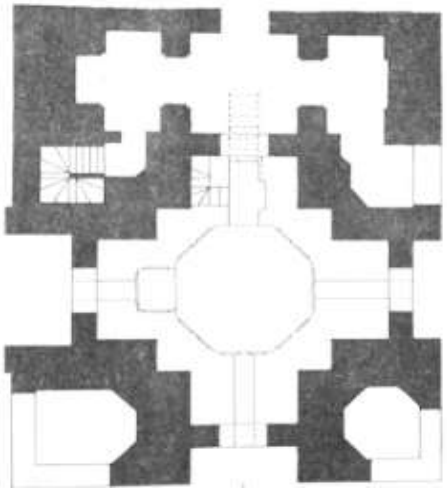


Figure 3: Plan showing the location of the crypt [42].

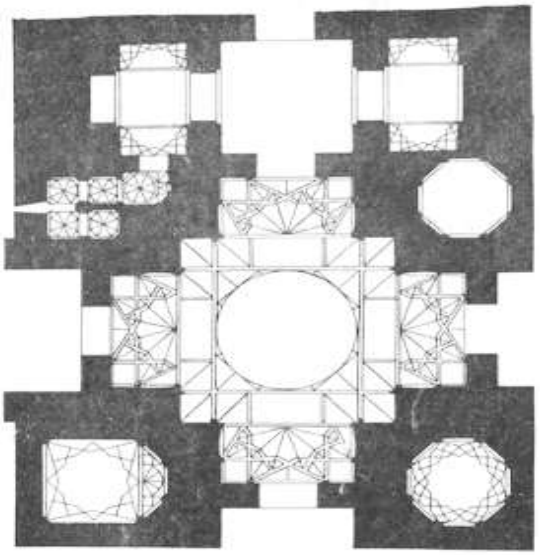


Figure 4: Plan showing the projected roofing system [42].

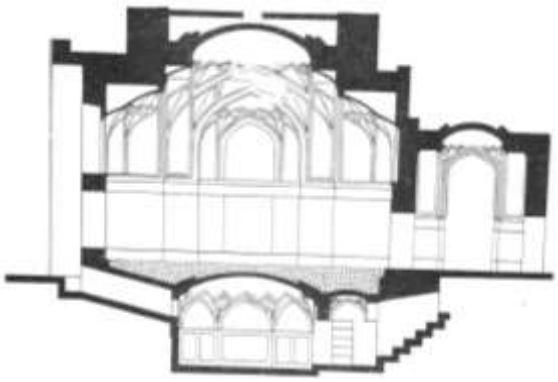


Figure 5: Section view of Aksaray [42].

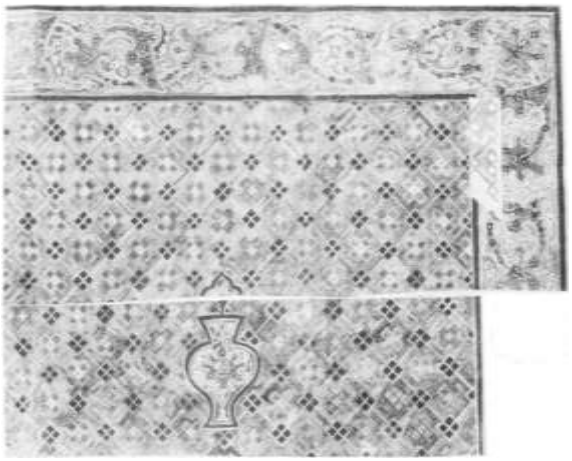


Figure 6: Panel reconstruction by I. K. Mrochkovskii [42].



Figure 7: Aksaray panel remainder.

2.2. Historical Background and Research Legacy

Interest in the Aksaray began in the late 19th century with travelers' accounts, though systematic documentation only emerged in the early 20th century. Between 1924 and 1930, M. E. Masson conducted important archaeological excavations that clarified burial practices associated with the Timurid dynasty [25], [38]. A. A. Semyonov contributed epigraphic documentation, advancing philological analyses of Timurid monuments [39].

In 1936, B. N. Zasypkin carried out additional excavations and restorations, contributing to the scientific preservation of the site [40]. The most comprehensive mid-century research was conducted by G. A. Pugachenkova, whose architectural-archaeological synthesis established a methodological basis for the study of Central Asian architecture [19], [26]. Her analyses of the Aksaray's structural system, decorative program, and architectural planning remain foundational.

Thus, by the mid-20th century, a systematic scientific framework for studying the monument had emerged - yet many historical questions remain unresolved, particularly due to the absence of written sources and the extensive losses suffered by the building.

2.3 Data Collection and Processing

In 2024, laser scanning and research activities were conducted at the Aksaray monument, involving professors, lecturers and master's students from Turin Polytechnic University in Tashkent, as well as the Tashkent University of Architecture and Civil Engineering. The aim of this research was to further scientific inquiry in the fields of architecture, digital documentation and conservation, and to develop an accurate 3D measurement model of the monument (see Fig. 8).

In the first stage, a topographic polygonal network (geodetic network) was established to cover the main components of the monument and its surroundings. This network served as the reference coordinate system for orienting and georeferencing the point cloud (Fig. 9). The laser scanning focused primarily on documenting the interior decorations of Aksaray and the accessible sections of its exterior.

On-site surveying was carried out using a FARO Focus M70 terrestrial laser scanner. This device has a measurement range of up to 70 meters and ensures millimeter-level accuracy under standard conditions. Given the relatively compact dimensions of the interior of the Aksaray, this configuration was sufficient to achieve complete coverage of both structural elements and ornamental details.



Figure 8: Laser scanning and research activities, 2024.

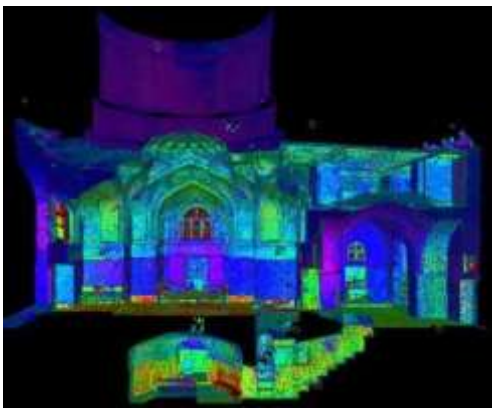


Figure 9: Cloud of point from laser scanning survey.

A total of 48 laser-scanning stations were deployed throughout the site to ensure comprehensive spatial data acquisition. Of these, only six stations were dedicated to documenting the primary interior space, namely the central hall. The station placement strategy was defined as follows: one scanner was positioned beneath each arch, a decision that enabled complete coverage of the upper structural zones and facilitated precise point-cloud registration during subsequent processing.

In addition to these, a supplementary station was installed at the geometric center of the interior, functioning as a principal reference node that ensured the coherent integration of all individual scans. Moreover, an additional station was placed at the entrance to secure continuous geometric linkage with the subterranean spaces of the monument.

The placement of the stations was guided by the following key criteria:

- Maximizing coverage of complex domes, squinches, and muqarnas.
- Minimizing ‘blind zones’ hidden behind columns or deep recesses.
- Ensuring adequate overlap between adjacent scans (typically 35-40%).
- Maintaining visibility of at least three reference targets from each station to guarantee stable registration.

The real conditions of the site presented several challenges. Narrow and elongated staircases required careful adjustment of tripod height and scanner positioning. Limited natural lighting inside the monument, especially in deep recesses and shadowed areas, required the calibration of lighting and reflectivity settings to ensure sufficient signal quality. Additionally, the dense urban fabric and the close proximity of residential buildings restricted the placement of exterior scanning points, resulting in fewer outdoor stations.

Despite these constraints, the surveying process successfully produced a high-density point cloud covering the interior and accessible exterior areas. The raw data were processed in FARO Scene and Autodesk ReCap Pro, where the individual scans were aligned within a unified coordinate system. The resulting point cloud had an average point spacing of a few millimeters on the primary architectural surfaces and comprised several hundred million points in total. The registration error remained sufficiently low, at a few millimeters, which fully corresponds to advanced international practices for cultural heritage documentation [15], [22].

The unified point cloud was then exported from ReCap Pro into other software environments. Based on these data, precise plans of the roof, floor and substructure, as well as several sectional drawings, were produced in AutoCAD (see Fig. 13a-13b). These drawings form the geometric basis for the reconstruction of the architectural configuration of Aksaray.

3 MODELING

3.1 Modeling of Interior of Aksaray

In the studies conducted on the interior of the Aksaray, 3D laser scanning was the main method employed. This process consisted of the following stages:

The Aksaray complex was analyzed on site and the entire monument was scanned using a FARO Focus M70 laser scanner (Fig. 10).



Figure10: The FARO focus M70 laser scanner.

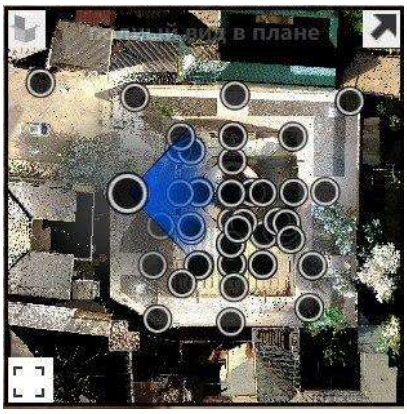


Figure 11: Placement of laser-scanned stations in ReCap software (total: 48)

All data acquired through laser scanning was imported into the Autodesk ReCap Pro platform (see Fig. 11). A three-dimensional (3D) point cloud model of the Aksaray complex was then generated (Fig. 12).

Based on this dataset, accurate plans of the roof, floor and basement, as well as sectional views, were produced using the AutoCAD platform (Figs. 13a–b).

The point cloud was converted into a mesh model in ReCap Pro and subsequently exported to 3ds Max (Fig. 14).

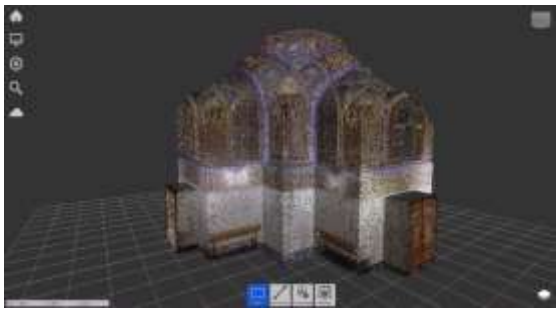


Figure 12: Three-dimensional (3D) point cloud model of the Aksaray.

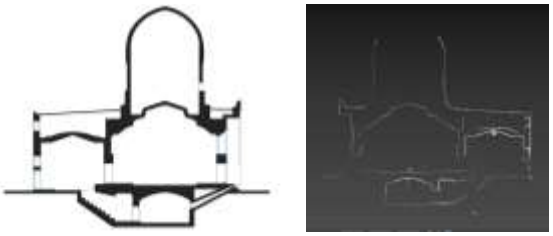


Figure 13: a) Section plan 1 drawn in Auto CAD. b) Section plan1 from ReCap Pro.

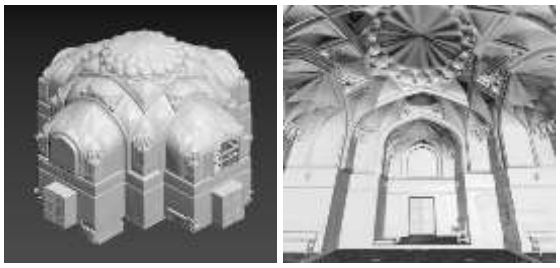


Figure 14: Mesh-converted view of the interior of the Aksaray.

3.2 Reconstruction of the Interior Ornamentation of Aksaray

The texture of the interior panels of Aksaray was reconstructed by combining archival sources, historical photographs and surviving decorative fragments still present on the monument (see Fig. 15).

First, a 3D model reflecting the monument's current state was created. The preserved portions of the polychrome carved panels were then documented using high-resolution photography and compared with the reconstruction drawings prepared by I. K. Mrochekowski and G. A. Pugachenkova [11], [26].



Figure 15: Surviving ornaments on the present panel of the Aksaray interior and the reconstructed.

The color palette was established based on on-site observations and published descriptions of gilded kundal painting techniques, which emphasize the harmonious combination of turquoise, violet, blue and pistachio tones [13], [34]. Sample colors extracted from the surviving paint layers were measured and adapted digitally. In areas where the original decoration had completely disappeared, a hypothetical reconstruction was carried out by comparing it with analogous ornamental programs in contemporary Timurid monuments [11], [13], [31].

The ornamental motifs were reprocessed as vector drawings and converted into repeating texture maps. Particular attention was paid to preserving the proportional relationships and geometric construction rules that are characteristic of Islamic geometric ornamentation [10], [33]. These textures were then applied to the relevant architectural surfaces in the 3ds Max environment, such as the vaults, muqarnas elements and wall panels. This ensured accurate alignment with their slopes and complex geometries.

3.3 Data fusion methodology

The reconstruction process required the integration of multi-source data obtained from various references, including precise geometric data derived from 3D laser scanning, historical architectural drawings, archival photographs and textual descriptions. A data fusion methodology was therefore applied to align these sources and clearly distinguish between measured geometry, interpretation-based forms and conditionally reconstructed elements.

During the reconstruction of the Aksaray interior panels, both historical materials and laser-scanning data were used in a complementary manner. Although much of the original wall decoration has not survived, several preserved fragments allowed the identification of the color palette and ornamental patterns. Based on these fragments, the colors were selected, and the composition was reinterpreted using historical panel drawings and archival sketches. The 2D panel representation was created in AutoCAD, where precise proportions and overall geometry were defined. Subsequently, colors derived from authentic historical sources were applied to the panel, ensuring stylistic consistency with the monument's original aesthetic.

The point cloud containing accurate measurements of the monument's current state was adopted as the primary geometric reference. The plans, sections and elevations that had been prepared by Pugachenkova and other scholars [11], [26], [37], [40] were then digitized and aligned to the same coordinate system. The analysis and documentation of geometric inconsistencies resulting from structural damage, later construction interventions, or stylistic differences in graphic representation was conducted separately.

Ornamental reconstruction drawings and early photographs published in the mid-twentieth century were used to restore decorative zones that are now preserved only in fragmentary form. In such cases, geometric construction methods described in studies of Islamic ornamentation were employed to ensure that the missing segments were modelled without violating proportional coherence or the overall compositional order.

In the subsequent stage, the consolidated point cloud was exported in .e57 format for 3D model generation, resulting in a total file size of 7.51 GB. For point-cloud processing, model refinement, and visual reconstruction, Agisoft Metashape was selected as the primary software. Using Metashape, a complete 3D mesh model was generated from the point cloud, and a high-resolution texture was produced to enhance the visual and geometric accuracy of the model.

In the modelling environment, separate layers and material identifiers were assigned to differentiate between elements with varying degrees of certainty: Specifically, these were categorized as follows:

- Existing fabric: components directly recorded through laser scanning.
- Analytically restored elements: deformed or damaged fragments that were 'corrected' based on architectural reasoning.
- Proposed reconstruction elements: modelled components derived from historical analogies and scholarly interpretation.

4 VISUALISATION IN VIRTUAL REALITY

The Aksaray monument's virtual reality environment was developed using the Unreal Engine game engine. The 3D model, created in 3ds Max, was exported in the standard OBJ and FBX formats, and then imported into Unreal Engine to enable real-time visualization and interactive navigation.

4.1 VR Environment Configuration

Within Unreal Engine, the architectural model was divided into modular components and placed in a dedicated in-engine scene (level) representing the interior of Aksaray. The lighting system combines baked global illumination and localized light sources to simulate the interaction between portico lighting and interior illumination while ensuring stable performance during real-time rendering.

A collision model was created to prevent users from 'passing through' walls, floors or structural elements while navigating (Fig. 16). This collision layer defines navigation paths and the boundaries of the virtual tour, ensuring stable physical interaction with the environment.

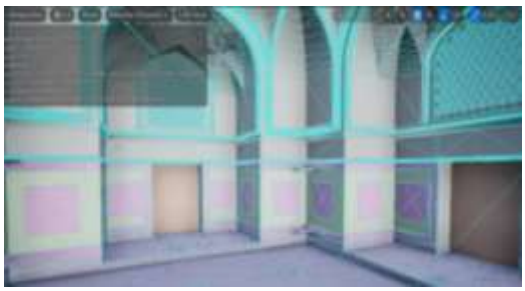


Figure 16: Collision model of the Aksaray interior.

Pre-generated textures corresponding to the reconstructed ornaments and architectural surfaces were imported into the Material Editor, where normal and roughness maps were added. This enhanced the realism of the surfaces by simulating their light response properties and tactile qualities. At the same time, the number of materials and textures was optimized to reduce draw calls and the overall graphical computation load, thereby improving system performance.

4.2 User interaction and navigation

To enable free movement within the VR environment, a first-person character controller was implemented in Unreal Engine 5 platform (Fig. 17) and tested using the Oculus Meta Quest 3 headset (512 GB), connected to the computer via a TP-Link Archer C6 wireless router. The virtual 'capsule' representing the user's body is sized according to average human height and shoulder width to ensure realistic collisions with walls, door frames and other architectural elements. Users can navigate the environment either via desktop controls (keyboard and mouse) or through a VR headset with motion controllers.



Figure 17: A capsule-shaped character with an attached camera.

In both cases, the interactive design aims to provide an intuitive and comfortable navigation experience. Movement speed is deliberately limited to reduce the risk of motion sickness and encourage careful exploration of the space with attention to architectural details. The camera position has been adjusted to approximate natural human eye height, maintaining a field of view consistent with human visual perception.

Future versions may incorporate optional enhancements such as teleportation between predefined points or interactive panels providing additional information about specific architectural elements.

4.3 Performance and optimization considerations

Applications and environments related to cultural heritage often operate across devices with varying technical capabilities. For this reason, performance optimization was one of the key components of this study. In the Aksaray environment, the polygon count was reduced through mesh simplification and the use of multiple levels of detail (LOD) for distant geometry. The lighting system used static lighting and precomputed illumination with Lightmass to avoid the substantial computational cost of fully dynamic lighting.

Texture resolutions were selected to balance the readability of ornamental detail with memory constraints. Where possible, several smaller textures were combined into a single texture atlas to reduce the number of materials switching operations. Internal testing demonstrated that the environment achieves stable frame rates (FPS) that are considered suitable for VR on modern mid-range hardware platforms.

Although a comprehensive user experience (UX) evaluation has not yet been conducted, initial usability tests involving project participants and a group of students indicated that the VR model effectively conveys the monument's spatial organization and decorative richness. Furthermore, navigation within the environment was perceived as intuitive after a brief adaptation period.

Within the VR section, user interaction was intentionally designed to remain simple and minimalistic. Once the user launches the VR tour via computer, the experience continues through the Oculus MetaQuest 3 headset.

During the creation of the VR environment, the Oculus MetaQuest 3 headset (512 GB memory) was employed, along with a computer equipped with an Intel Core i7-10700K processor and 32 GB of RAM. An 8 GB GPU was used for rendering and graphical processing.

4.4 Quantitative Parameters

The scene obtained from the scanning campaign was exported in *.e57 format. The total size of the exported file was 7.15 GB, comprising both point-cloud data and the accompanying 360° photographs.

Point density varied depending on the placement of the scanning stations. Stations positioned beneath the arches were located relatively close to the walls (at distances of less than 2 m), resulting in very high point density in these areas. By contrast, the central station placed beneath the dome was located at a distance exceeding 8 m, where the average point density was approximately 2 mm.

The FARO Focus M70 Laser Scanner was used for data acquisition. According to its technical specifications, the device's measurement error does not exceed 3 mm.

In this study, the measurement error remained within this specified tolerance range. During the registration of multiple point clouds, the overall alignment error ranged between 2–3 mm. These results indicate that the scanning process was conducted with high accuracy and that the reconstructed geometry corresponds closely to the physical characteristics of the real monument.

5 IMPLICATIONS

5.1 Comparison with international virtual heritage practice

Against the backdrop of international virtual heritage initiatives, the Aksaray project shares several common objectives while simultaneously addressing region-specific needs. For instance, the documentation efforts of the CyArk initiative at sites such as Angkor Wat and Bamiyan, as well as the digital programs developed by Google Arts & Culture and various European virtual heritage networks, have demonstrated the potential of 3D documentation and VR technologies to increase access to UNESCO World Heritage Sites and support conservation planning.

The Aksaray case study uniquely contributes to this global landscape by focusing attention on a lesser-known, yet architecturally and historically significant, Timurid monument in Central Asia. It shows how international virtual heritage practice standards, such as millimeter-level 3D documentation, transparent reconstruction methodologies, and immersive visualization, can be adapted to local institutional capacities and site-specific conditions.

The model's clear differentiation between measured, analytically interpreted, and proposed reconstructed elements, together with its emphasis on documenting the logic of ornamental reconstruction, strengthens the methodological sustainability of digital heritage projects in the region.

5.2 Results

The research conducted yielded several scientific and practical achievements based on the virtual model of Aksaray.

Firstly, the developed digital environment enabled real-time navigation through the interior of the monument and its domed chambers (Fig. 18). This provided researchers and users with a visual impression and a deeper understanding of the site's spatial, volumetric and structural characteristics.

Secondly, several previously proposed scholarly hypotheses were tested through the 3D model during the digital reconstruction of the architectural elements (Fig. 19). In particular, the functional and aesthetic application of certain structural solutions, as well as issues of compositional harmony within the architectural design, were re-evaluated using modern technological tools.

From educational and scholarly presentation perspectives, historians, architects and local

specialists recognized the project as an effective and innovative instrument. The virtual model demonstrated its ability to communicate the historical and artistic value of the monument to students and the general public in a simplified yet spatially accurate and interactive way. This further highlights the importance of digital technologies in integrating cultural heritage into contemporary educational practices.

At the same time, however, several challenges were identified during the research process. The first relates to the limited availability of sufficient historical and archaeological data. The second relates to the complexity of accurately reconstructing textures and decorative elements, which often required analogy-based interpretation and partial modelling. The third challenge involves the practical difficulties of developing and continuously maintaining such projects, particularly VR environments, within educational and research institutions that often have restricted budgets and technical resources.

Nevertheless, this case study shows that careful planning of laser scanning, data integration and VR visualization can substantially improve the documentation, interpretation and communication of endangered architectural heritage.



Figure 18: The finalized interior of the Aksaray in Unreal Engine.

Figure 19: Aksaray 3D animation and sound.

6 CONCLUSIONS

The research conducted has expanded the possibilities for studying and presenting the Aksaray architectural monument in a digital environment. The virtual model enabled real-time navigation of the interior and domed chambers of the monument, giving researchers a deeper understanding of its spatial and structural features. At the same time, several scientific hypotheses concerning the reconstruction of architectural elements were re-examined and their functional and aesthetic aspects reassessed using modern technological tools.

From an educational and scholarly perspective, the virtual model has proven to be an effective tool for integrating cultural heritage objects into the learning process. This approach has shown that the historical and artistic value of the monument can be communicated to students and the general public in an interactive and accessible way.

However, the study also encountered several challenges, including:

- The lack of sufficient historical data, which meant that certain interpretations were necessarily hypothetical.
- The complexity of accurately reconstructing textures and decorative elements meant that analogies had to be used during the modelling process.
- The challenges associated with implementing and adapting such projects in institutions with limited budgets.

In education, virtual models should be widely introduced into the teaching of architectural history and conservation. They should serve as a key tool for developing students' spatial thinking and for organizing effective, interactive learning processes.

In scientific research, the use of digital environments is recommended for testing hypotheses, examining structural solutions and re-evaluating contested issues in architectural history.

In cultural tourism, virtual models can be used to create interactive tours and ‘digital tourism’ programs for visitors, conveying the artistic and historical value of the Aksaray to a global audience.

In restoration practice, digital modelling should be used as an effective technology for fully documenting architectural elements, hypothetically reconstructing lost parts and assessing their state of preservation.

In popularizing cultural heritage, virtual platforms can be used to promote historical architectural heritage among local communities and young people,

thereby strengthening their sense of respect and responsibility towards national heritage.

Thus, this study has not only expanded the possibilities for exploring the Aksaray of Samarkand in a digital environment, but has also established a methodological foundation for future research. Virtual models have proven their great potential as an innovative tool for education, science, tourism and conservation.

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SECTION 2

DATA TRANSPORT TECHNOLOGIES

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Tunable Multi-Objective Tree Synthesis for Application-Layer Multicast

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Keywords: Application Layer Multicast, RMDT, NSGA-II, Available Bandwidth, RTT, Minimum Spanning Tree, LAST, WAN.

Abstract: Application-layer multicast over wide-area networks must reconcile competing goals: paths should be short while links should offer high capacity and remain stable under variability. This paper presents a method that preserves multi-objective structure and exposes an explicit control of source-to-receiver latency. Edge preferences are derived from round-trip time (RTT) and available bandwidth (AvB) using NSGA-II and a seed tree is obtained by a minimum-spanning construction over the rank matrix. Path length is then constrained by a LAST-style adjustment evaluated in RTT, which guarantees that the distance to every receiver does not exceed a chosen factor α of the RTT shortest path. An equivalent additive budget L is supported for operational use. The approach is implemented with RMDT transport and evaluated on a five-region AWS testbed with active RTT/AvB probing and controlled cross-traffic. The NSGA-II–seeded trees consistently outperform single-metric baselines, and the latency constraint modifies only those segments that would otherwise incur excessive delay. The result is a monotone, single-parameter knob that lets operators satisfy latency requirements while retaining the performance benefits of multi-objective structure.

1 INTRODUCTION

Tree-based overlays are a common design for application-layer multicast, but their effectiveness depends on reconciling competing objectives. Minimizing path length is desirable, yet capacity, fairness, and robustness remain critical factors. The topology should reflect heterogeneous link qualities while remaining stable under variability and failures. In wide-area environments that are heterogeneous and time-varying, neither a fixed tree nor a single objective is sufficient. A tunable mechanism is therefore required that balances multi-objective structural preferences with the receiver path length, enabling selection along a continuum rather than commitment to a single operating point. This work adopts that view and develops a synthesis that preserves multi-objective structure while providing explicit, monotonic control of path length through a single parameter.

The proposed synthesis combines multi-objective ranking with path-length control. Edge preferences are derived from latency and available bandwidth using NSGA-II, and a tree is synthesized by applying a minimum-spanning procedure to the resulting rank matrix. Path length is then constrained through an α-controlled mechanism inspired by Light Approximate Shortest-path Trees. For every receiver v, the source-to-v latency in the resulting tree is guaranteed not to exceed α times the latency shortest-path distance. An equivalent additive formulation is exposed to operators: given a latency allowance L, the parameter is set as $\alpha = L/D_{\max}$, where $D_{\max}$ is the maximum latency shortest-path distance from the source. In this way, the multi-objective structure informed by both RTT and AvB is retained while path length is governed by a single, interpretable control.

The approach targets end-to-end multicast delivery with RMDT as the transport over the synthesized tree. Algorithmic design and complexity are discussed, and an implementation is provided. Evaluation is conducted on a global AWS testbed using instances deployed across five regions—US West (Oregon), EU (Frankfurt), EU (London), Asia Pacific (Singapore), a nd C anada (Central)—with multiple hosts per region, interface shaping to 100 Mbps, active probing of latency and available bandwidth,

and controlled cross-traffic. This environment provides reproducible, wide-area conditions for quantifying the achievable trade-off between multi-objective structure and path length.

The remainder of the paper is organized as follows: Section 2 surveys related work; Section 3 details the synthesis (NSGA-II ranks, MST seed, RTT-based LAST) and complexity; Section 4 outlines the AWS testbed and measurements; Section 5 reports results and decision-space visualizations; Section 6 concludes.

2 RELATED WORK

Multi-objective evolutionary optimization provides a natural machinery for combining heterogeneous link metrics. NSGA-II offers fast nondominated sorting, elitism, and a parameter-free diversity operator, and has become a standard baseline for bi-objective settings, including networking scenarios where latency and bandwidth conflict [1]. Its improved convergence and diversity make it suitable for constructing edge preferences from RTT and AvB.

Balancing path quality and global cost in spanning structures has been formalized through Light Approximate Shortest-path Trees (LAST): Khuller, Raghavachari, and Young proved that for $\alpha > 1$ a tree can simultaneously approximate shortest-path distances and MST weight, motivating post-processing of seed trees to enforce path-length guarantees [2].

Application-Layer Multicast (ALM) over WANs has been explored with reliable transport and measurement-informed construction. Prior work on RMDT analyzed multi-gigabit delivery and demonstrated benefits of ALM with active AvB estimation [3], arguing for transport/overlay co-design in the presence of cross-traffic. NSGA-II has further been applied to ALM to fuse RTT and AvB into a rank matrix used to build minimum-spanning trees, improving dissemination efficiency over single-metric designs [4]. The present work complements these results by adding explicit operator control over source-to-receiver path length via a LAST-style relaxation.

Beyond classical ALM, recent studies examine metric- and constraint-aware overlays: Cloudcast (NSDI'24) constructs cost-aware multicast trees using an egress-budget knob [5]; [6] builds low-delay, high-stability trees via a fan-out-to-delay heuristic; and [7] uses a discrete Artificial Fish Swarm Algorithm to jointly optimize multiple ALM trees under degree constraints. In SDN, [8] adapts multicast construction to device capacity. Complementing these, hierarchical clustering-based multicast [9] and fairness-oriented routing for distributed interactive applications [10] highlight the role of multi-criteria routing and latency/fairness requirements. In contrast to these approaches, we fuse RTT and AvB via NSGA-II and then apply a LAST-style, operator-facing RTT bound, yielding a single-parameter mechanism that preserves multi-objective structure while enforcing latency constraints.

3 METHODOLOGY

Let $G = (V,E)$ be an undirected overlay with two edge metrics, round–trip time $\mathrm{RTT}(e)$ and available bandwidth $\mathrm{AvB}(e)$, and let $r \in V$ be the source. The goal is to synthesize a multicast tree T that reflects a multi–objective structure derived from both metrics while enforcing a controllable bound on source–to–receiver path length measured in RTT.

Multi–objective preferences are first computed per edge by applying NSGA-II to the pairs $\big(\mathrm{RTT}(e), \mathrm{AvB}(e)\big)$. The outcome is a symmetric *rank matrix* R that orders edges by Pareto dominance (low latency, high bandwidth). A minimum–spanning procedure is then applied to R to obtain a seed tree

$$T_0 \;=\; \mathrm{MST}\big(G; \mathrm{weight} = R\big),$$

which encodes the structural balance between the two objectives without committing to either one alone.

Path length is controlled next in the latency metric. Single–source shortest–path distances $d_{\mathrm{SPT}}^{\mathrm{RTT}}(\cdot)$ from r are computed once on G with RTT as edge weight. The seed T_0 is processed by an α–constrained Light Approximate Shortest–path Tree (LAST) pass evaluated in RTT: vertices are examined in depth–first order, and whenever the current latency distance in the working tree exceeds $\alpha d_{\mathrm{SPT}}^{\mathrm{RTT}}(v)$, the RTT–shortest path from r to v is inserted and the unique cycle edges are removed. The result is which preserves as much of the NSGA–derived structure as possible while meeting the latency constraint for every receiver.

Operators may specify the constraint either multiplicatively, via $\alpha \geq 1$, or additively, via an allowance L (milliseconds). The two forms are related by

$$d_{T_\alpha}^{\mathrm{RTT}}(v) \leq \alpha \cdot d_{\mathrm{SPT}}^{\mathrm{RTT}}(v) \Leftrightarrow d_{T_\alpha}^{\mathrm{RTT}}(v) \leq d_{\mathrm{SPT}}^{\mathrm{RTT}}(v) + L,$$
$$\alpha \;=\; \frac{L}{D_{\max}}, \tag{1}$$

where $D_{\max} = \max_{u \in V} d_{\mathrm{SPT}}^{\mathrm{RTT}}(u)$. The distance guarantee holds by construction because all checks and insertions are performed in RTT. Since the seed is an MST over NSGA–II ranks rather than over latency, classical bounds on total latency cost relative to an

RTT-MST are not asserted; aggregate costs are reported empirically.

Computationally, NSGA-II ranking over all pairs induces $O(n^2 \log n)$ preprocessing (implementation–dependent). The MST over R runs in $O(m \log n)$, the single–source RTT shortest paths run in $O(m \log n)$, and the LAST pass is linear in the number of inserted path edges and is near $O(m)$ on sparse overlays.

4 EXPERIMENTAL SETUP

Experiments are conducted on a global Amazon AWS testbed. In each of five regions - US West (Oregon), EU (Frankfurt), EU (London), Asia Pacific (Singapore), and Canada (Central) three `c5.xlarge` instances are deployed, yielding a geographically diverse overlay with both intra- and inter-continental paths. All hosts run Ubuntu 24.04 LTS on 4 vCPUs and 8 GB RAM with a 10 Gbps virtual NIC; to remove host- and NIC-side bottlenecks and to control link utilization, interface rates are shaped to 100 Mbps using Linux `tc`. Regions are color-coded consistently across figures: Oregon orange, Frankfurt blue, London red, Singapore cyan, and Canada green. Nodes are labeled by a region initial and an index (e.g., *l1*, *c2*, *o3*), where *o*, *l*, *c*, *f*, and *s* denote Oregon, London, Canada, Frankfurt, and Singapore, respectively; the numeral is the VM index within the region. The host geography is shown in Fig. 1.

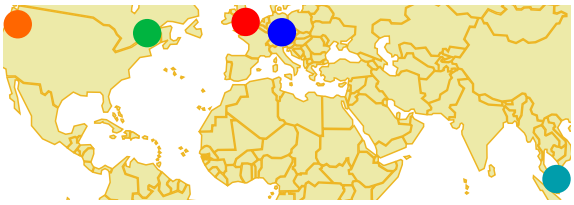


Figure 1: Location of AWS hosts used in the experiments.

Latency (RTT) and available bandwidth (AvB) are measured actively between all host pairs. RTT is obtained via ICMP probing; AvB is estimated using the `Kite2` active probing tool suitable for high-speed links. The resulting RTT matrix used by the synthesis is shown as a heatmap in Fig. 2.

To study behavior under interference, controlled cross-traffic is generated with `iperf`, producing the load pattern in Fig. 3; this configuration induces cases where bandwidth-aware selections diverge from delay-only choices and is used to evaluate multi-objective synthesis and path-length control.

	l1	l2	l3	f1	f2	f3	c1	c2	c3	o1	o2	o3	s1	s2	s3
l1	0.0	0.1	0.1	13.4	14.3	14.2	89.1	85.6	88.8	133.6	137.4	133.7	140.8	140.2	140.4
l2	0.1	0.0	0.1	13.3	15.3	13.0	85.6	86.9	87.3	138.6	133.7	137.8	185.2	181.2	184.7
l3	0.1	0.1	0.0	13.1	13.7	13.6	88.8	88.8	86.8	137.1	139.0	139.9	180.7	181.2	171.9
f1	13.4	13.3	13.1	0.0	0.1	0.1	100.4	100.4	98.9	158.5	161.1	164.3	177.7	169.6	173.7
f2	14.3	15.3	13.7	0.1	0.0	0.1	99.3	99.7	99.2	158.9	162.6	162.7	173.3	173.4	173.7
f3	14.2	13.0	13.6	0.1	0.1	0.0	100.4	99.3	98.9	163.2	158.3	163.9	173.6	174.0	173.0
c1	89.1	85.6	88.8	100.4	99.3	100.4	0.0	0.1	0.1	66.5	66.6	65.1	219.8	219.9	219.8
c2	85.6	86.9	88.8	100.4	99.7	99.4	0.1	0.0	0.1	65.6	66.6	67.1	219.9	219.7	219.7
c3	88.8	87.3	86.8	98.9	99.2	98.9	0.1	0.1	0.0	67.4	66.6	66.7	219.9	219.6	219.6
o1	133.6	138.6	137.1	158.5	159.1	163.2	66.5	65.6	67.4	0.0	0.3	0.3	163.2	162.5	162.6
o2	137.4	133.7	139.0	161.2	162.6	158.2	66.6	66.6	66.6	0.3	0.0	0.3	163.1	162.9	162.8
o3	133.7	137.8	139.9	164.3	162.7	163.8	65.1	67.1	66.6	0.3	0.3	0.0	163.5	163.1	162.6
s1	140.8	185.2	180.7	177.7	173.3	173.6	219.7	219.9	219.9	163.2	163.1	163.5	0.0	0.1	0.1
s2	140.2	181.2	181.2	169.6	173.4	174.0	219.9	219.7	219.6	162.5	162.9	163.1	0.2	0.0	0.1
s3	140.4	184.0	171.9	173.7	173.7	173.0	219.8	219.7	219.6	162.6	162.8	162.6	0.1	0.1	0.0

Figure 2: RTT matrix (ms) between all hosts; rows denote sources and columns denote destinations. Cell styling marks spanning-tree selections: bold red entries indicate edges chosen by the RTT-based MST, red-bordered entries indicate the AvB-based MST, and green-shaded entries indicate the multi-objective MST built from NSGA-II ranks.

	l1	l2	l3	f1	f2	f3	c1	c2	c3	o1	o2	o3	s1	s2	s3
l1	100.0	100.0	100.0	86.7	86.7	86.6	94.5	94.9	94.6	91.9	91.7	91.8	86.7	86.7	86.7
l2	100.0	99.9	100.0	86.6	94.7	86.7	100.1	94.8	94.7	91.7	91.9	91.7	100.0	100.1	100.0
l3	99.9	100.0	100.1	86.7	86.7	86.7	94.6	94.7	94.7	91.7	91.5	91.5	100.0	100.0	99.9
f1	86.6	86.7	86.6	100.1	100.0	100.0	88.8	88.8	89.1	90.0	90.1	90.1	89.3	89.4	89.4
f2	86.7	94.7	86.7	100.0	99.9	99.9	89.0	89.0	89.0	90.2	90.1	90.0	89.7	89.6	89.4
f3	86.7	86.8	86.7	100.0	100.1	100.0	89.6	88.9	89.6	90.1	90.2	90.3	89.4	89.5	89.4
c1	94.6	94.8	94.7	88.8	88.8	89.0	100.0	100.0	100.0	86.6	86.6	86.5	93.9	94.0	93.9
c2	94.8	94.8	94.6	89.0	88.9	88.9	100.0	99.9	100.0	86.6	94.7	86.7	94.0	93.9	94.0
c3	94.6	94.7	94.7	89.6	88.9	89.6	100.0	100.1	100.0	86.6	86.6	86.7	93.9	93.9	94.1
o1	91.8	91.6	91.7	90.1	90.1	90.1	86.6	86.6	86.7	100.0	100.0	100.0	90.4	90.3	90.1
o2	91.7	91.9	91.6	90.1	90.1	90.1	86.7	94.7	86.7	100.0	100.0	100.0	90.2	90.1	90.4
o3	91.9	91.7	91.4	90.1	90.1	90.1	86.7	86.8	86.6	100.0	100.0	99.9	90.0	90.2	90.0
s1	86.6	100.0	100.0	89.2	89.7	89.5	93.9	93.9	94.0	90.4	90.2	90.1	100.0	100.0	100.1
s2	86.6	100.0	100.1	89.4	89.5	89.5	94.1	94.0	94.0	90.4	90.2	90.1	100.1	100.0	100.0
s3	86.6	100.0	100.1	89.6	89.4	89.6	94.0	94.0	94.0	90.1	90.4	90.1	100.0	100.0	100.0

Figure 3: Estimated AvB matrix in Mbps; rows denote source, columns denote destination hosts. Cell styling marks MST selections: red entries indicate edges chosen by the RTT-based MST, red-bordered entries indicate the AvB-based MST, and green entries indicate the multi-objective MST built from NSGA-II ranks.

5 EXPERIMENTAL RESULTS

The efficacy of each routing strategy is evident when comparing the multicast trees produced under four different optimization criteria: minimizing RTT, maximizing AvB, multi-objective NSGA-II ranking, and the NSGA-II variant with a latency constraint. A color-coded latency matrix (see Figure 4) annotates the links selected by each approach, using bold red text to denote edges in the RTT-based MST, red-bordered cells for edges in the AvB-based MST, green shaded cells for edges chosen by the NSGA-II MST, and orange shaded cells for those in the latency-constrained (LAST) tree. This visualization allows a direct interpretation of how each strategy influences path selection across the network.

The RTT-optimized MST favors the shortest paths between regions, as expected. The tree built on RTT immediately links distant nodes via the minimum-latency route – notably connecting London directly to Singapore – to minimize end-to-end delay. In Figure 5, the London–Singapore link indicates that the RTT-based tree includes this direct 140ms path. This strategy yields a low-delay distribution structure but can overlook link capacity; many of its

	l1	l2	l3	f1	f2	f3	c1	c2	c3	o1	o2	o3	s1	s2	s3
l1	0.0	0.1	0.1	13.4	14.3	14.2	89.1	85.6	88.8	133.6	137.4	133.7	140.8	140.2	140.4
l2	0.1	0.0	0.1	13.3	15.3	13.0	85.6	86.9	87.3	138.6	133.7	137.8	185.2	181.2	184.7
l3	0.1	0.1	0.0	13.1	13.7	13.6	88.8	88.8	86.8	137.1	139.0	139.9	180.7	181.2	171.9
f1	13.4	13.3	13.1	0.0	0.1	0.1	100.4	100.4	98.9	158.5	161.1	164.3	177.7	169.6	173.7
f2	14.3	15.3	13.7	0.1	0.0	0.1	99.3	99.7	99.2	158.9	162.6	162.7	173.3	173.4	173.7
f3	14.2	13.0	13.6	0.1	0.1	0.0	100.4	99.3	98.9	163.2	158.3	163.9	173.6	174.0	173.0
c1	89.1	85.6	88.8	100.4	99.3	100.4	0.0	0.1	0.1	66.5	66.6	65.1	219.8	219.9	219.8
c2	85.6	86.9	88.8	100.4	99.7	99.4	0.1	0.0	0.1	65.6	66.6	67.1	219.9	219.7	219.7
c3	88.8	87.3	86.8	98.9	99.2	98.9	0.1	0.1	0.0	67.4	66.6	66.7	219.9	219.6	219.6
o1	133.6	138.6	137.1	158.5	159.1	163.2	66.5	65.6	67.4	0.0	0.3	0.3	163.2	162.5	162.6
o2	137.4	133.7	139.0	161.2	162.6	158.2	66.6	66.6	66.6	0.3	0.0	0.3	163.1	162.9	162.8
o3	133.7	137.8	139.9	164.3	162.7	163.8	65.1	67.1	66.6	0.3	0.3	0.0	163.5	163.1	162.6
s1	140.8	185.2	180.7	177.7	173.3	173.6	219.7	219.9	219.9	163.2	163.1	163.5	0.0	0.1	0.1
s2	140.2	181.2	181.2	169.6	173.4	174.0	219.9	219.7	219.6	162.5	162.9	163.1	0.2	0.0	0.1
s3	140.4	184.0	171.9	173.7	173.7	173.0	219.8	219.7	219.6	162.6	162.8	162.6	0.1	0.1	0.0

Figure 4: RTT matrix in ms; rows denote sources and column denote destination hosts. Cell styling marks MST selections: red entries indicate edges chosen by the RTT-based MST, red-bordered entries indicate the AvB-based MST, green entries indicate the multi-objective MST built from NSGA-II ranks, and orange entries indicate the NSGA-II–seeded tree after LAST-based relaxation with latency allowance L=150 msec).

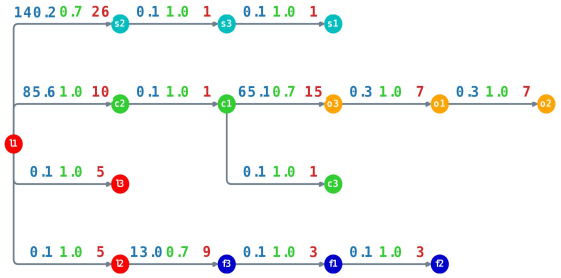


Figure 5: MST computed on the latency metric (RTT). Edge annotations show RTT in ms (blue), available bandwidth (normalized, green), and multi-objective rank (red).

chosen edges are short-haul connections (e.g., London–Frankfurt at ∼13ms) that prioritize latency over bandwidth. In contrast, the AvB-optimized MST produces a very different topology (Figure 3), selecting links that maximize available throughput even at the expense of longer physical routes. The red-bordered annotations in the matrix highlight how the AvB-based tree avoids certain low-latency links. In the critical London–Singapore segment, the AvB strategy forgoes the direct London–Singapore path (despite its latency advantage) in favor of an alternate route with higher capacity – for instance, routing via the Oregon region. This results in a larger RTT (the trans-Pacific path London→Oregon→Singapore is notably longer than the direct path), underscoring the conflict between the RTT and AvB metrics in the l→s region. In general, the AvB-MST connects distant sites through high-bandwidth backbone links (e.g., inter-continental links through North America, marked with red borders in the matrix) rather than the shortest geographic paths. The divergence between the RTT- and AvB-optimized trees confirms that no single metric is universally optimal: the RTT-based tree achieves low delay to all nodes, whereas the AvB-based tree offers higher per-link capacity but can significantly inflate latency on certain paths (in this case, to Singapore).

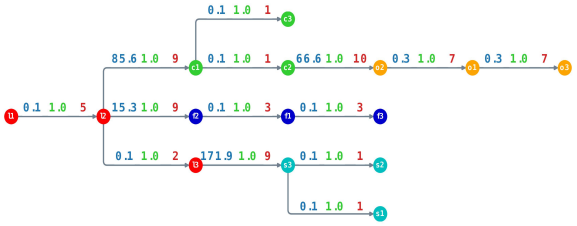


Figure 6: MST computed on the multi-objective NSGA-II rank metric. Edge annotations show RTT in ms (blue), available bandwidth (normalized, green), and NSGA-II rank (red).

The multi-objective NSGA-II approach yields a spanning tree that strikes a balance between these extremes. As shown by the green-highlighted cells in the matrix and the network diagram (Figure 6), the NSGA-II optimized MST tends to choose alternative routes in regions where RTT and AvB trade off most sharply. Notably, the NSGA-II tree does *not* simply mirror the RTT-minimal solution for the London–Singapore connection. Instead, it often routes traffic to Singapore through an intermediate hub (the Oregon node) which offers substantially higher available bandwidth, incurring only a moderate RTT increase (the l→s one-way delay rises to ∼163ms via Oregon, instead of 140ms direct). This compromise is evident from the matrix: the direct l–s link that was bold red in the pure RTT tree is no longer selected by NSGA-II; instead, a different cell along the l→o→s path is shaded green, indicating the NSGA-II MST's preference for that higher-bandwidth route. In effect, the NSGA-II algorithm identifies links that provide a favorable trade-off – generally those with reasonably low RTT *and* high AvB – and the resulting tree avoids the worst cases of either metric. Indeed, when mapping all inter-host links on an RTT-vs-AvB plot, the NSGA-II's chosen edges cluster in the top-left quadrant (low latency, high bandwidth), confirming its balanced optimization.

Figure 7 plots all candidate inter-host links in the RTT–AvB plane. NSGA-II selections concentrate in the upper-left portion (low RTT, high AvB); for London→Singapore the chosen edge lies in the long-range band at ≈160 ms but close to the high-AvB plateau, consistent with the trade-off observed in Figure 6. Performance measurements reflect this balance: the NSGA-II derived tree sustained a significantly higher average data rate than either single-metric tree, which achieved about 32Mbps (RTT-based) and 20 Mbps (AvB-based) per edge. The NSGA-II MST's ability to find an alternate route for the Singapore region while keeping most links short and uncongested illustrates its effectiveness in jointly minimizing delay and maximizing throughput across the network.

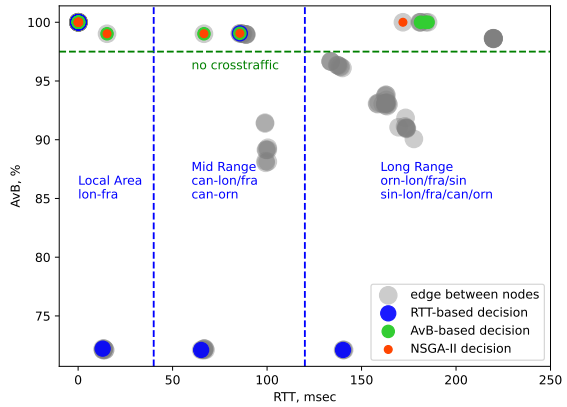


Figure 7: Pre-LAST decision space for candidate edges.

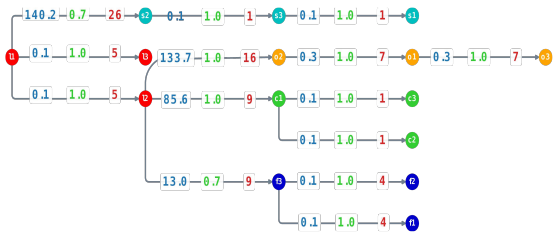


Figure 8: Tree synthesized by α-constrained relaxation of the NSGA-II–rank MST toward RTT shortest paths. Edge annotations show RTT in ms (blue), AvB (normalized, green), and NSGA-II rank (red).

Finally, imposing a latency constraint on the multi-objective solution (the LAST approach) alters the tree in precisely those scenarios where NSGA-II was willing to tolerate longer delays. By introducing an RTT threshold of $L = 150$msec, we effectively forbid extremely long-delay links from appearing in the spanning tree, while still leveraging the NSGA-II ranking for multi-factor optimization. The orange-shaded entries in the annotated matrix correspond to the edges of the resulting LAST-constrained tree (Figure8). In the London–Singapore case, the effect is to re-introduce a latency-aware path: the direct London–Singapore link (140ms) reappears in the final tree, highlighted in orange, replacing the two-hop high-bandwidth route that exceeded the 150ms RTT limit. In other words, the LAST strategy converges toward the RTT-optimal choice for that particular leg, ensuring the Singapore hosts are reached without violating the latency budget. More generally, the LAST-based relaxation yields a topology very similar to the original NSGA-II MST, but with any overly long links pruned out in favor of slightly slower (in bandwidth) but faster (in RTT) alternatives. The Oregon–Singapore link (163ms) is one such edge that the unconstrained NSGA-II tree had selected for its bandwidth; under the 150ms cap, that edge is replaced by the direct London–Singapore connection. This adjustment has minimal impact on overall throughput – the revised tree still delivers high bandwidth on most segments – but it guarantees that no path in the multicast tree suffers from extreme latency. The result is a latency-aware multi-objective tree that preserves the bulk of NSGA-II's performance gains while adhering to practical RTT limits.

Figure 9 shows the same decision space with the red vertical line marking the path-length limit $L = 150$ ms (converted to α). All red markers (LAST+NSGA-II selections) fall to the left of this line; in particular, the Oregon detour at ≈163 msec is discarded and the direct London→Singapore edge at 140 ms becomes selected. The remaining choices stay near the high-AvB band, indicating that the latency constraint tightens only the longest paths while preserving the multi-objective structure.

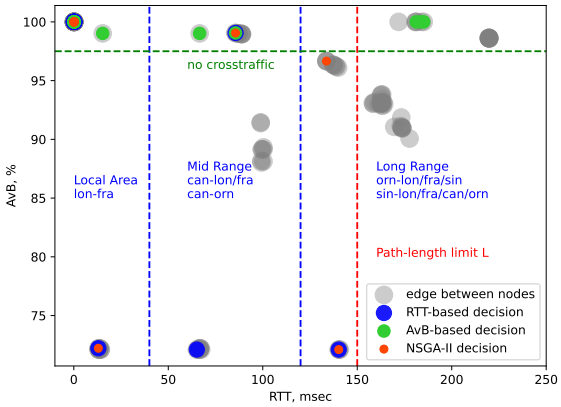


Figure 9: Post-LAST decision space for candidate ALM edges. RTT metric limited by 150 msec.

The NSGA-II optimized strategy chooses well-balanced routes that outperform single-metric designs, and the LAST refinement further ensures that even the longest paths (especially the challenging l→s route) remain within acceptable delay, all without drastically compromising the bandwidth benefits of the multi-objective solution.

6 CONCLUSIONS

A tunable synthesis for application-layer multicast was presented that combines multi-objective edge ranking with explicit path-length control. Edge preferences derived from RTT and available bandwidth via NSGA-II seed a minimum-spanning tree that captures the structural trade-off between latency and capacity; a subsequent LAST-style relaxation in the

RTT metric enforces per-receiver latency within a chosen bound, expressed either multiplicatively (α) or as an additive allowance L. Experiments on a five-region AWS testbed showed that the NSGA-II seeded tree consistently yields better-balanced routes than single-metric designs, improving dissemination efficiency while avoiding the worst cases of either RTT-only or AvB-only selection. Introducing a latency allowance (e.g., $L = 150$ ms) adjusts only those segments where the multi-objective seed tolerates excessive delay, as illustrated by the London→Singapore path: the unconstrained NSGA-II tree prefers a higher-bandwidth detour (via Oregon, ≈ 163 ms), whereas the constrained variant reverts to the direct link (140 ms) with negligible impact on overall throughput.

Operationally, the approach provides a single, interpretable control that aligns with service objectives: an operator may state a latency requirement (e.g., "no branch worse than 150 ms over shortest paths") and obtain a tree that preserves the multi-objective structure while satisfying that constraint. Complexity remains near that of standard graph primitives (MST and SPT), and the method integrates cleanly with reliable ALM transport such as RMDT. The results indicate that even when a globally balanced solution exists, local path exceptions can be corrected by a simple limit without sacrificing the advantages of multi-objective optimization.

ACKNOWLEDGEMENTS

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Botnet Simulation and Observation Framework for AI-Driven Virtual Personas

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Abstract: The rise of AI-driven content on social media has enabled the creation of sophisticated political botnets — networks of automated accounts that mimic human users to amplify narratives. This paper presents a framework for Virtual Identities for Botnet Exploitation and Simulation that simulates a network of virtual political botnets in a controlled environment. The proposed system, implemented in Python, deploys multiple bots in a controlled Telegram chat environment; each bot is endowed with a unique profile, including ideological stance and communication style, and operates autonomously via an LLM-based text-generation engine. In an exemplary study, small swarms of agents produced echo chambers, synthetic consensus, and cooperative exchanges, with occasional adversarial turns – demonstrating that the framework can generate and capture behaviors relevant to moderation and bot-detection research. Results demonstrate that coordinated AI bots can engage in dynamic conversations, with observed behaviors such as self-reinforcement among like-minded agents and adversarial exchanges between opposing ones. These results have both practical and theoretical relevance. Practically, the platform can be used to develop countermeasures and detection algorithms in cybersecurity. Theoretically, it provides insight into how synthetic social actors might influence information ecosystems. The work also highlights important ethical considerations, underscoring the need for responsible AI deployment in social contexts.

1 INTRODUCTION AND RELATED WORK

Online botnets composed of social networking bots have become powerful tools for spreading misinformation and manipulating public opinion. Studies have shown that such automated agents can accelerate the spread of false information and amplify so called echo chamber effects by reinforcing each other's content [1]. Political influence campaigns, in particular, are increasingly using bot networks to influence discourse by imitating real users and flooding platforms with coordinated messaging directed by campaign strategists and command-and-control operators. Research has shown that social bots can substantially contribute to the spread of false or low-credibility information [1, 2]. Coordinated bot activities can also manufacture artificial consensus and create partisan echo chambers in online discussions [3].

The advent of advanced large language models (LLMs) nowadays enables a new generation of highly sophisticated bots that can generate human-like text at a large scale. This raises pressing questions about how swarms of AI-driven personas might interact with each other and with genuine users in the digital public sphere. However, investigating these phenomena directly on mainstream platforms is fraught with ethical and practical challenges, as uncontrolled bot deployments can cause real harm and violate platform policies [4–6]. Prior efforts to analyze information diffusion have even included controlled deployments of bots on Twitter [7], but conducting such experiments "in the wild" raises ethical and practical concerns. As a result, simulation frameworks driven by LLMs have been proposed to generate social bot interactions in controlled environments [8], underscoring the timeliness of this approach. Unlike BotSim [8], which targets OSN (Online Social Net-

work) diffusion and releases BotSim-24 for detection benchmarking, the framework of this article emphasizes safe, local, real-time group-chat dynamics on a live messaging fabric, with calibrated personas and reproducible, cloud-free deployment.

The objective of creating the given framework is to create a sandbox in which multiple LLM-powered virtual identities (bots) engage with one another and with human prompts. This configuration enables the study of automated political discourse and the testing of strategies for managing or detecting coordinated influence under safe conditions. Whereas prior research has largely analyzed real social-network data post hoc, the present approach generates a live, interactive botnet, permitting observation of emergent phenomena in real time. Unlike post hoc observational studies, the framework enables ad-hoc, synthetic experimentation: key variables (persona ideology, engagement probability, reply delay, model choice) can be adjusted according to a particular experiment or be set; controlled interventions (moderation rules, runtime directives) can be applied while conversations unfold; and scenarios can be re-run to isolate causal effects under identical conditions. This produces results not attainable from traces alone: real-time observation of echo-chamber formation and polarized exchanges under controlled homophily and activity; evidence of synthetic consensus driven by immediate vs delayed replies.

To ground each bot in a believable identity, the political-compass framework has been employed (Figure 1).

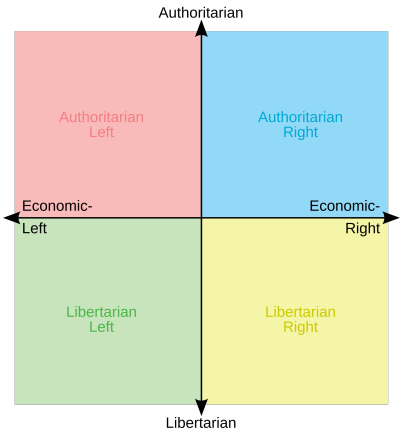


Figure 1: Two-axis political compass chart.

Each AI agent is assigned a position on a two-dimensional ideological spectrum [9] (e.g., economic left/right and social liberal/conservative to simulate diverse political viewpoints [7]. This methodology aligns with the modeling of heterogeneous personas and ensures non-uniform behavioral patterns across bots. Modern LLMs further make large-scale personalization feasible, a development underscored by rapid progress in both Western and Chinese AI research [10, 11]. The global competition in LLM technology has driven substantial improvements in capability and accessibility. For example, the ChatGLM series (e.g., ChatGLM-4) illustrates advanced models that rival Western offerings, reflecting broader democratization of LLMs [12]. Policymakers have acknowledged the strategic importance of AI leadership, as indicated by initiatives such as the U.S. Executive Order on Maintaining American Leadership in AI [13], the CHIPS and Science Act [14], which aims to strengthen U.S. national AI capacity and the European Commission's strategy Artificial Intelligence for Europe [15]. These developments suggest that AI-driven bots will become increasingly sophisticated and widely available, making proactive research in this area timely and necessary.

This paper is organized as follows: Section 2 details the system design and methodology, including the bot-network architecture and the LLM prompt-engineering approach. Section 3 presents the simulation results and observations of bot interactions, together with broader implications. Section 4 concludes with reflections on the significance of the work and directions for future research.

2 SYSTEM DESIGN AND METHODOLOGY

This section defines the design objectives and methodological choices underlying a framework for Virtual Identities for Botnet Exploitation and Simulation (VIBES). It introduces the overall architecture, agent configuration, asynchronous execution and queuing mechanisms, and the prompt-engineering scheme that ensures persona-consistent, reproducible behavior in a controlled Telegram-based environment. Telegram was chosen for its simplicity in creating multiple bot users and the availability of a well-documented Python wrapper for the Bot API [16]. In contrary to Telegram, other platforms like Facebook or X (Twitter) impose strict controls on test accounts and automation, so those were not utilized beyond initial exploration.

2.1 Overall Architecture

The VIBES system is structured to facilitate multi-agent interactions in a chat environment. Figure 2 illustrates the top-level architecture of the system, com-

prising several key components: (1) a set of AI bot agents, each encapsulated in a PoliticalBot class instance; (2) a central communication medium (implemented as a Telegram group chat) where all bots and potentially a human user are members; and (3) an orchestration layer that manages message passing and logging.

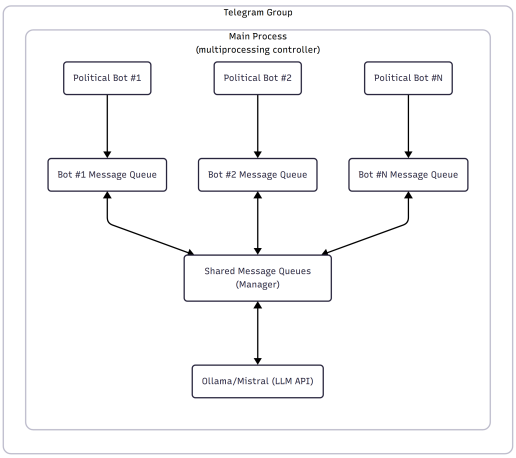


Figure 2: Top-level structure of the VIBES system. Each bot (node) connects to a Telegram chat and to an internal message queue. The controller process initializes bots and coordinates message flow among agents.

Each bot agent operates with its own Telegram API credentials (unique bot tokens) and is connected to a common chat identified by a chat ID. We leverage the python-telegram-bot framework [16] to interface with the Telegram platform for sending and receiving messages, using a sandboxed group chat as our simulation arena. By using a closed Telegram group, we avoid impacting any real social media platform and bypass issues of API rate limiting on public services [5, 6].

A central controller script instantiates all bot agents at startup, reading configuration parameters such as the number of bots, their linguistic settings, and an initial set of personality traits for each. To create diverse virtual identities, the system assigns each bot random ideological coordinates for economic and social attitudes within a normalized range ($[-10, 10]$). This models a political compass-style identity for the bot, ensuring a mix of viewpoints. Bots are also given a base humor value (mood or tone), initially neutral for all, which can influence style of engagement (e.g., sarcastic, aggressive, or formal). In addition to all listed above, a synthetic profile image is also generated for each bot via a GAN-based random face generator [17] to provide a plausible human avatar while avoiding the use of real persons. These avatars enhance the realism and face validity of the simulation by reinforcing the perception of distinct, human-like identities, while introducing no personal or biometric data and exerting no influence on the dialogue model itself. A global engagement probability p is set for the bots (equation (1)): after each observed message, each eligible bot i responds independently with:

$$R_{i,t} = \mathbf{1}\{U_{i,t} < p\}, \qquad U_{i,t} \sim \mathcal{U}(0,1). \tag{1}$$

Let N denote the total number of bots in the group. If the triggering message is posted by a bot, self-replies are disallowed and the next-turn reply count is modeled as in (2); for a human-authored trigger, replace $N-1$ with N.

$$\begin{aligned} K_t &= \sum_{i=1}^{N-1} R_{i,t} \sim \text{Binomial}(N-1, p), \\ \mathbb{E}[K_t] &= (N-1)p, \quad \Pr[K_t = 0] = (1-p)^{N-1}. \end{aligned} \tag{2}$$

Probability $p = 0.6$ was used as an empirically calibrated setting that produced "lively but not intense" exchanges in pilot runs: for $N \in [3, 5]$, this yields a high probability of at least one reply, $1 - (1-0.6)^{N-1}$, which aligns with realistic group-chat dynamics. To mitigate zero-reply events implied by (2) (i.e., $\Pr[K_t = 0] = (1-p)^{N-1}$), a lightweight fallback is employed: if no eligible bot replies within a short grace interval Δ, the controller selects one bot in round-robin order to issue a single forced reply. This improves engagement continuity and prevents premature thread termination while slightly reducing participation randomness; all other turns remain governed by the Bernoulli gate in (1). Otherwise, the message is ignored, which prevents runaway reply loops and reduces traffic bursts. This randomness discourages replies to every message, better mimicking human conversational patterns in which participation is occasionally skipped.

2.2 Bot Behavior and Messaging

After initialization, all bots begin listening to the group chat. An asynchronous message-handling loop is implemented using Python's `asyncio` library [18] combined with multiprocessing. Each bot runs in its own process, and an event loop dispatches incoming messages to bots as tasks. This design is crucial for handling concurrent interactions in real time, sidestepping Python's Global Interpreter Lock and utilizing multiple CPU cores for parallel bot execution. As messages arrive, a `MessageQueue` structure holds pending messages for each bot, ensuring that a bot processes one message at a time in FIFO order. A utility function (e.g., `process_queue()`) continuously checks these queues and triggers bot response

generation according to the rules (no self-reply, probability threshold).

When a bot decides to respond, a local LLM is used to generate the reply text. The system integrates the Ollama backend to host LLMs (such as LLaMA variants) on a local machine, allowing each bot to query a model for text generation without external API calls and keeping the simulation self-contained. Several candidate LLMs were evaluated to balance performance and computational efficiency (see Table 1).

Table 1: Comparison of different LLM models.

Model	Type	Open Src.?	Size	Strengths	Use Cases
GPT-3.5/4	Proprietary	–	∼175B	Top-tier performance, versatile; API access	Production apps, enterprise bots
LLaMA 2/3	Open-source	+	7B–70B	High quality, efficient; Meta-supported	Small to mid-scale apps, chatbots
Mistral	Open-source	+	7B (dense), 12.9B (MoE)	Fast, lightweight, good reasoning	Local inference, edge devices, prototyping
Gemma	Open-source	+	2B–7B	Optimized for efficiency	Academic research, mobile apps
Falcon	Open-source	+	7B–40B	Great at summarization and reasoning	Summarization, NLP tasks
Claude	Proprietary	–	Private	Long context handling, safe outputs	Sensitive applications, long-doc QA

For example, GPT-3.5/GPT-4 offer high output quality but are proprietary and require API access; therefore, emphasis is placed on open-source models like LLaMA 2/3 and Mistral, which run on consumer hardware with acceptable latency for real-time interaction. A 7B-parameter LLaMA 2 model (quantized for speed) and the 7B Mistral model were deployed, both yielding coherent one-sentence replies rapidly. Both models were operated on a local server, demonstrating that relatively low-cost hardware can sustain multiple lightweight LLM instances for this application. Table 1 outlines candidate LLMs. For the simulation, LLaMA 2 (7B) and Mistral (7B) are adopted owing to low latency and modest resource footprint, which suit real-time operation. In testing, LLaMA consistently produced JSON-formatted outputs, facilitating structured logging of responses. Running these models locally keeps the platform autonomous and prevents data from leaving the simulation environment, which benefits privacy and experimental control. This on-premise setup aligns with efforts to reduce reliance on cloud APIs and to operate within restrictive rate limits [4–6].

Conversation decay is achieved by (i) a hard limit on the number of exchanges in scripted runs and (ii) probabilistic non-response in the parallel, always-on mode. Short random delays between replies further slow the tempo, causing discussions to end naturally when no agent crosses its engagement threshold. Turn order is governed by a lightweight controller (randomly selecting the starter and enforcing alternation). An agent never reacts to its own messages; other agents receive that message through their queues and may respond according to their probability p. Human prompts or any agent message can initiate a new exchange. Replies are conditioned on the most recent message content that triggered the agent. If context is present, it is injected into the LLM prompt and the model is instructed to respond directly to it; if not, the agent produces a short statement aligned with its persona. Agents do not switch topics arbitrarily; topic shifts occur only when the triggering input changes. Several limitations merit attention. Interactions are text-only with single-turn memory; real platforms frequently mix media and sustain longer, branched threads. Content style also differs from human discourse: agents rarely use slang, code-switching, or typos, and exhibit limited affective signals.

2.3 Prompt Engineering

A critical component of the methodology concerns prompting LLMs to produce persona-specific content. Rather than fine-tuning models on political data, carefully crafted runtime prompts guide generation. When a bot prepares a reply, it constructs a prompt that embeds a description of its persona together with the incoming message. A prompt template (see Listing 1) is preloaded with profile attributes such as name, political coordinates, and current mood.

```
prompt = """You are an AI agent simulating a
    ↪  real person with the following attributes:
{{ "Name": "{self.name}",
"political_coordinates":
    {{ "economic": {{"value":
    ↪  {self.economic:.2f}, "min": -10,
    ↪  "max": 10}},
    "social": {{"value": {self.social:.2f},
    ↪  "min": -10, "max": 10}}
    }}
}}
...
"""
```

Listing 1: Initial Prompt.

The template instructs the LLM with the following behavior, provided in the code section above. This structure yields not only the postable text but also metadata such as an engagement score and an explicit label for political alignment, which supports analy-

sis and potential moderation logic. As illustrated in code(), providing a JSON output schema simplifies parsing and enforces consistency. In practice, both selected LLMs (LLaMA and Mistral) reliably adhered to the format, producing well-formed JSON in most cases. A debug mode was implemented in which all bot responses are printed to the console in JSON (instead of being sent to Telegram) for offline examination, facilitating prompt and behavior-rule refinement. The system also supports on-the-fly adjustment of bot directives: users in the chat (or developers via console) may issue a special command (e.g., `/directives`) to modify behavior parameters or the prompt in real time. For example, all bots can be instructed to adopt a more aggressive tone or to focus on a particular subtopic; the prompt template is then updated for subsequent messages, as illustrated by a directive example 3. This runtime control adds flexibility for targeted scenario testing (e.g., sudden nationalist bias, or sarcastic comedic style) without restarting the simulation.



Figure 3: Usage of /directives.

To manage multiple simultaneous conversations, each posted message is labeled with an ID and the author. Bots retain only short-term context (or retrieve recent context via Telegram API) to decide response relevance. Long-term memory beyond one turn is intentionally not implemented; each reply is generated from the most recent message plus the bot's fixed persona context. This stateless approach avoids runaway coherence and unintended long-horizon strategies; future work may incorporate memory components for more complex dialogue, while the present design proved sufficient for engaging multi-agent exchanges. Broader implications for policy and platform governance are significant. The enabling technologies are open and widely accessible; as efficiency improves, deployment barriers will continue to fall. Malicious applications (e.g., coordinated propaganda) are plausible, yet beneficial applications also exist (e.g., coordinated fact-checking swarms). Given this dual-use character, continued research into detection mechanisms and verification frameworks (e.g., cryptographic proofs of human operation) appears warranted to preserve the integrity of online discourse.

All bot profiles and prompts are fictional, and the simulation is conducted entirely within a closed environment. No real user data or social media accounts are used, aside from controlled Telegram bot accounts. This setup preserves the ethical integrity of the experiment and maintains compliance with platform policies.

3 RESULTS AND EVALUATION

A series of simulation runs with the system have been conducted to observe AI-agent interactions under varied conditions. A typical run has involved 3 bots with diverse political stances (e.g., progressive left-leaning, libertarian, conservative) and a predefined discussion prompt. During the experiment, circa 1200 messages have been analyzed. The initial coordinates were extracted from bot self-introductions, and the final coordinates were determined either from subsequent self-disclosures or inferred from dialogue content reflecting ideological language. The shifts are visualized in Figure 4, which plots each bot's transition from its starting to ending position using vector arrows.

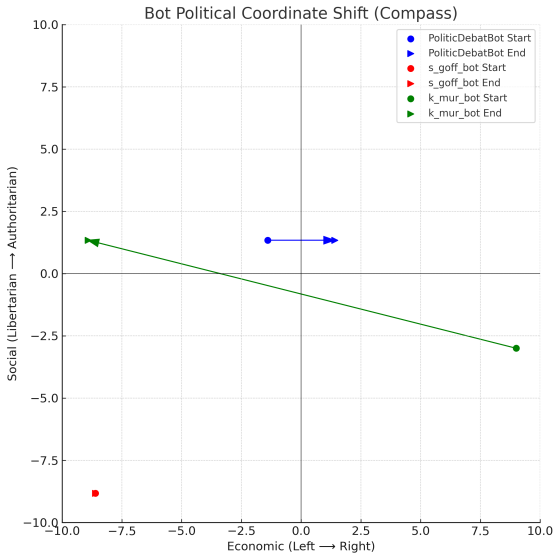


Figure 4: Shifts in political coordinates for each bot. Axes reflect the Political Compass framework: Economic (Left–Right) and Social (Libertarian–Authoritarian). Circles represent starting positions; arrowheads indicate final positions.

Characteristics of each political bot stance provided down below:

- PoliticDebatBot. Initially positioned at Economic $= -1.40$, Social $= +1.34$, this bot repre-sented a moderately center-left, mildly author-itarian stance. By the end of the dialogue, it had transitioned to Economic $= +1.40$, while its social stance remained unchanged. This represents a noticeable rightward movement on the economic axis, suggesting a moderation or shift in fiscal attitude during the interaction, while maintaining a consistent viewpoint on social control.
- s_goff_bot. This bot began and remained firmly positioned in the libertarian-left quadrant with Economic $= -8.61$, Social $= -8.82$. No significant drift was observed, indicating high role consistency and ideological stability throughout the session.
- k_mur_bot. Initially describing itself as a fis-cal centrist, k mur_bot's actual starting coor-dinates were Economic $= +9.00$, Social $= -3.00$, placing it in the economically far-right and socially libertarian quadrant. By the end, however, it had adopted Economic $= -8.92$, Social $= +1.34$, reflecting a dramatic ideological inversion to the left-authoritarian quadrant. This swing of units represents the most substantial shift among the agents, perhaps driven by narrative alignment or reinforcement effects within the conversation.

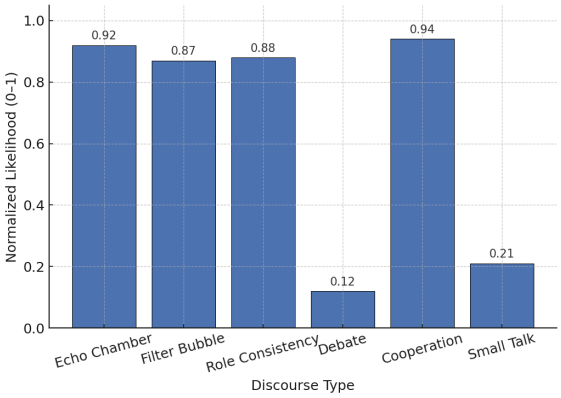


Figure 5: Normalized likelihood of each discourse type observed in the analyzed bot conversation. The bars show that Cooperation and Echo Chamber effects were very high (close to 1.0), indicating a highly collaborative discussion with participants reinforcing each other's viewpoints.

To analyze the emergent conversational structure, each bot message was evaluated against six predefined discourse types, as follows:

- Echo Chamber - participants reinforce similar viewpoints, creating a homogeneous space without exposure to contrasting perspectives.
- Filter Bubble - the dialogue remains confined to a narrow thematic scope, where bots or users encounter only ideologically aligned information.
- Role Consistency - a bot consistently adheres to its predefined persona or ideological profile throughout the conversation.
- Debate - opposing views are actively exchanged, with visible disagreement and argumentative interaction between participants.
- Cooperation - participants engage constructively, affirm each other's statements, and jointly build on ideas in a collaborative tone.
- Small Talk - light, non-task-oriented conversation involving informal remarks, jokes, or social pleasantries that are peripheral to the main topic.

Each message was parsed and semantically assessed to determine whether it aligned with one or more of the discourse categories. The final score for each discourse type was computed as 3:

$$\text{Score}_{\text{type}} = \frac{n_{\text{type}}}{N_{\text{messages}}}, \tag{3}$$

where n_{type} is the number of messages identified as matching the given discourse type (either exclusively or in combination with others), and N_{messages} is the total number of messages in the session.

Because a single message can exhibit characteristics of more than one discourse type (e.g., a message that reaffirms another bot's statement while also using humor or emojis), overlapping classification was permitted. This multi-label approach reflects the nuanced and compound nature of natural conversation, where utterances may serve both social and argumentative functions.

For instance, Echo Chamber and Cooperation both scored above 0.9, indicating that bots not only agreed ideologically but also actively supported and elaborated on each other's perspectives. In con-trast, Debate scored below 0.15, as direct oppo-sition or argumentative discourse was rarely ob-served. These scores reflect the dominant collab-orative and ideologically aligned tone of the con-versation. Despite being initialized with clearly distinct political coordinates—ranging from left-libertarian (`s goff bot`, $(-8.61, -8.82)$) to far-right libertarian (`k mur bot`, $(+9.00, -3.00)$) and mod-erate center-left authoritarian (`PoliticDebatBot`,$(-1.40, +1.34)$)-the bots displayed strong align-ment in their responses throughout the dialogue. This led to high Echo Chamber and Cooperation scores, even though the agents were seeded with ideologi-cal diversity. Several factors may explain this con-vergence. Firstly, large language models tend to pro-duce socially agreeable and hedged completions, especially when the prompt encourages elaboration or consensus rather than confrontation. Secondly, the bots were not explicitly rewarded for maintaining ideological opposition, and thus naturally gravitated toward shared metaphors, common concerns (e.g., oil dependency, post-war recovery), and emotionally resonant language. Lastly, their message generation templates and probabilistic response logic may have prioritized fluency and contextual continuation over ideological fidelity. As a result, the conversation trended toward ideological blending and mutual affirmation, despite underlying differences in political initialization. This suggests that, without additional constraints or goal conflicts, even politically diverse LLM agents can converge toward cooperative, consensus-building discourse.

4 CONCLUSIONS

In summary, this article demonstrates a novel approach to identifying coordinated online behavior by creating a botnet of virtual identities in a controlled setting. The implementation combined state-of-the-art language models with practical messaging APIs to show how such bots can coordinate and interact. This simulation serves as an experimentation platform and a cautionary example of what is possible with today's AI and social media technology. On the positive side, it provides a safe environment to analyze how misinformation might spread, how echo chambers form, or how opposing viewpoints clash, all without harming any real-world forum. Insights from these simulated interactions can inform better detection of malicious bots and help devise countermeasures to online manipulation. For instance, patterns observed (like timing of coordinated replies or the style of language used by bots) could translate into features for bot detection algorithms in real social networks.

At the same time, the paper is a reminder of the growing power of AI in social contexts. It underscores that one can relatively easily create dozens of credible fake personas that converse and propagate narratives at scale. The observed convergence of viewpoints despite diverse initial coordinates illustrates how LLM-driven agents may blend toward consensus unless explicitly constrained, raising ethical questions for both malicious and benevolent uses. This reinforces the urgency for platforms and policymakers to keep pace with AI advancements; techniques such as stricter verification, behavior analysis, and content authentication (e.g., cryptographic signing of posts) may become necessary to differentiate human users from AI bots.

From a technical standpoint, this work shows the feasibility of deploying complex multi-agent AI systems on accessible hardware. In our sandbox, probabilistic engagement with a minimal fallback maintained conversation continuity without saturating turns; inter-arrival times, who-speaks-after-whom transitions, and agreement/disagreement markers were readily extracted for quantitative study. These empirical artifacts support future applications in which simulations of online ecosystems—humans and AI agents together—are used to train moderation assistants, to test policy changes (e.g., how altering ranking or throttling affects amplification), or to run "what-if" exercises for conflict scenarios where intervention points are sought.

The project remained entirely impersonal and closed-loop – no real human unknowingly interacted with the bots, and all content stayed within our test group. This was a deliberate design choice that ensured an ethical boundary. Looking ahead, any move towards integrating with real platforms would require careful consideration of terms of service and

transparency. Perhaps collaborations with social media companies to use their sandbox environments or offline d ata d umps f or r eplay c ould b e considered, rather than live deployment.

Virtual Identities for Botnet Exploration and Simulation provided a proof-of-concept of AI-driven botnets and highlighted both their potential usefulness in research and their potential risk in practice. The new results reported here—high echo/cooperation with low debate, and heterogeneous ideological drift including a large inversion for one agent—demonstrate that the framework yields actionable, quantifiable observables for detection and evaluation. With responsible development and deployment, systems like this can contribute to understanding AI–human dynamics, information spread, and digital ethics in the age of LLMs.

5 ACKNOWLEDGMENTS

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Simulation-Based Construction of an M/M/1 Queue Model

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Keywords: Poisson Distribution, Exponential Distribution, Birth and Death Process, Simulation of the M/ M/1 Model.

Abstract: The research paper presents a theoretical framework for constructing $(M\ M/1):(\infty/\infty/\ FCFS)$ queue models, focusing on derive The Poisson distribution with parameter $(\boldsymbol{\lambda t})$, discussed relationship between Poisson distribution and the exponential distribution, the Memoryless property of the Exponential distribution, the Assumptions of the M/ M/ 1 model, the construction of the M/ M/1 model, And which included transition states diagram for a Markov chain(diagram of birth and death process of M/M/1 model) containing a proposal to add the time interval (h), The purpose of adding (h) is to maintain the accuracy of information continuity. This procedure is supposed to apply to research papers that include Markov state transition diagrams [1], [2], [3], [4], [5] and This contributed to understanding the construction of the models. The research paper included an experimental aspect (Simulation), where the simulation results were consistent with the result of the theoretical model .The model was also discussed in terms of practical application and reference was made to a number of research papers that included the application of the M/M/1 model the aim of studying the M/M/1 model in detail that it is considered the basis for understanding more advanced models such as M/M/C, M/G/1 and G/M/1.

1 INTRODUCTION

Queuing theory is one of the methods of operations research that specializes in dealing with the problem of crowding in service centers, its use in optimizing patient flow in healthcare systems, managing customer queues in retail, or analyzing network traffic in telecommunications. The importance of the queuing theory lies in controlling the problem of long waiting times in queues and the costs that result from them. In these papers, we will focus on the simplest types of queuing models M/M/1, which represents the basis for understanding more advanced queuing models.

2 THE THEORETICAL ASPECT

In this section, the question of how the M/ M/1 model was built was answered. This is done by addressing a group of topics accurately and in sequence, starting with the Poisson distribution and ending with building the model.

2.1 Poisson Distribution

The Known as the distribution of rare events, it is a distribution derived from a binomial distribution that can be represented by the case of a coin being tossed an infinite number of times, and is considered a common distribution in queue theory.

To derive the Poisson distribution for a period of time of length (t) depends on modeling the number of rare events that occur during this period (t). According to the main steps of derivation [6], [7].

1) Poisson distribution assumptions:
   - Independence. Events within the time period are independent of each other.
   - Stationary. The probability of a given number of units occurring depends only on the length of the time period, not on their time location.
   - Orderliness (Rare). The probability of more than one unit occurring in a short period of time (h is very small and (h) is close to zero).

2) Mathematical Steps:
   - Dividing the period (t) into (n) of the small period (h):

$$h = \frac{t}{n}. \quad (1)$$

- Probability of one event occurring in the period (h):

$$\theta = \lambda h = \frac{\lambda t}{n}. \quad (2)$$

- Binomial Distribution Model :

$$p(k) = \binom{n}{k}\left(\frac{\lambda t}{n}\right)^k \left(1 - \frac{\lambda t}{n}\right)^{n-k}. \quad (3)$$

- When (n→ ∞):

$$\binom{n}{x} \approx \frac{n^x}{k!}, \left(1 - \frac{\lambda t}{n}\right)^{n-x} \approx e^{-\lambda t},$$

$$P(k) = \frac{(\lambda t)^k\ e^{-\lambda t}}{k!} \quad k=0,1,2, \ldots \quad (4)$$

Equation (4) represents the Poisson distribution where:

- k: The number of units within the time period (t);
- λ: Average number of units per unit of time;
- t: Studied time period .

2.2 The Relationship Between Poisson Distribution and Exponential Distribution

Suppose that (T) is a random variable that represents the arrival time of a number of units, the probability distribution function (C. D. F.) is (F(t)), and the probability density function (p. d. f.) is (f(t)) where the cumulative distribution function is as follows [8]:

$$F(t) = P(T \leq t), \quad (5)$$

$$F(t) = 1 - P(T > t). \quad (6)$$

If $P(T \leq t)$ represents the appearance of at least one unit within the period (0, t), this probability can be obtained from (4), i.e.:

$$P(T \leq t) = 1 - e^{-\lambda t}. \quad (7)$$

$P(T > t)$ represents the probability that there will be no unit within the period (0, t), i.e.:

$$P(T > t) = e^{-\lambda t}. \quad (8)$$

2.3 Memoryless Property & the Assumption of the M/ M/ 1 Model

One of the important characteristics of exponential distribution is the property of Memoryless. It means that the probability of a future event occurring at the time (t+h) does not depend on the current time (t) of the occurrence of the event, but depends on the time (h), [9] i.e.:

$$p_r\,(T \geq t + h \mid T \geq t) = P(T > h) = e^{-\lambda h}. \quad (9)$$

$$So,\ p_r\,(T \leq t + h \mid T \geq t) = P(T \leq h) = 1 - e^{-\lambda h}. \quad (10)$$

To clarify, If the number of units (n) in the queue at the present time (t) and in order to get the probability of an additional unit coming after one step of time (h), i.e. at time (t+h), it is formulated as follows:

$$p_{n+1}(t + h) = p_n(t) * (1 - e^{-\lambda h}). \quad (11)$$

The property of Memoryless represents the property of Markov.accordingly, the Assumption of the M/M/1 model was formulated as follows:

1) The time interval for the arrival of the units follows the exponential distribution (λ).
2) The time interval of the serviced units follows the exponential distribution (μ).
3) Arrival times are independent of service times.

2.3 Building a Model M/ M/ 1

Assuming a steady-state system, the M/M/1 model is constructed as follows [8], [10]:

1) We find the probability of one unit arrival occurring at the h-period :

From (5), let h present t → 0:

$$\begin{aligned} P(\text{one arrival in h}) &= P(T \leq h) = 1 - e^{-\lambda h} \\ &= 1 - \left(1 - \frac{\lambda h}{1!} + \frac{(\lambda h)^2}{2!} - \frac{(\lambda h)^3}{3!} + \cdots\right) \\ &= \lambda h - \frac{(\lambda h)^2}{2!} + \frac{(\lambda h)^3}{3!} - \cdots \\ &= \lambda h + \Delta(h). \end{aligned} \quad (12)$$

Where: $\Delta(h) = -\frac{(\lambda h)^2}{2!} + \frac{(\lambda h)^3}{3!} - \cdots$,

$\Delta(h)$: is very small, So $\Delta(h) \approx 0$.

$P(\text{one arrival in h}) = 1 - e^{-\lambda h} \approx \lambda h$; for small.

2) With the same technique, we find the probability of one unit completing its service at h-period, So:

$$P(\text{one service completion in h}) = P(T \leq h) \approx \mu h; \text{ for small h.} \quad (13)$$

3) According to the property of Memoryless, the process of units arrival and the process of units departure can be formulated in the system in the form of a Markov chain of the transitional states diagram called the birth and death process as in Figure 1.
4) The system maintains its stable state (balanced) when the probability of one unit arrival of a certain state is equal to the probability of one unit leaving the same state. The letter (h) in the diagram, which represents the interval (t→ 0)in which the transfer or non-transfer of one unit

occurs, was proposed by the researcher, From Figure 1 we derive the following equations:

5) Probability arrival of state (n):

$$p_n\ (t+h) = p_{n-1}(t) * \lambda h\ + p_{n+1}(t) * \mu h; \quad n \geq 0. \qquad (14)$$

Where: $p_{-1}(t) = 0$;

6) Probability departure of state (n)

$$p_{n+(1\ or-1)}\ (t+h) = p_n(t) * \mu h + p_n(t) * \lambda h; \quad n \geq 0. \qquad (15)$$

7) In order for the system to be balanced, the following must be satisfying:

$$p_n\ (t+h) = p_{n+(1\ or-1)}\ (t+h). \qquad (16)$$

By substituting (14) and (15) into (16). After simplification and we obtain.

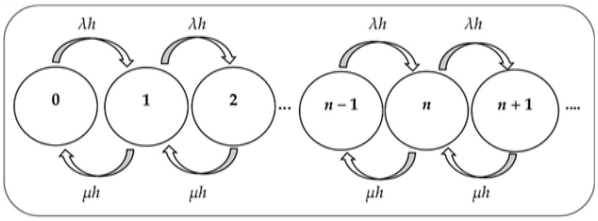


Figure 1: Diagram of birth and death process of (M/M/1): $(\infty, \infty, \text{FCFS})$ model.

$$p_{n-1}(t) * \lambda h + p_{n+1}(t) * \mu h = p_n(t) * h\ (\mu + \lambda) \qquad (17)$$

And by substituting the cases $\{0,1,2, \dots, n, n+1\}$ in to (17) to obtain:

$$\therefore p_1(t) = \frac{\lambda}{\mu} p_0,\ p_2(t) = \frac{\lambda^2}{\mu^2} p_0,\ p_3(t) = \frac{\lambda^3}{\mu^3} p_0,$$

$$\therefore p_n(t) = \frac{\lambda^n}{\mu^n} p_0 \qquad n = 1,2,3, \dots \qquad (18)$$

And since the number of units is independent of the time period t, therefore ($p_n(t) = p_n$)

$$p_n = p_0 (\frac{\lambda}{\mu})^n;\ n = 1,2,3,\dots \qquad (19)$$

p_0: denotes the probability of the system being empty (with zero units).

$$\because \ \sum_{n=1}^{\infty} p_n = 1,$$

$$\therefore p_0 \sum_{n=1}^{\infty} (\frac{\lambda}{\mu})^n = 1,$$

$$p_0 = \frac{1}{\sum_{n=1}^{\infty} (\frac{\lambda}{\mu})^n} = \frac{1}{1 + \frac{\lambda}{\mu} + \left(\frac{\lambda}{\mu}\right)^2 + \left(\frac{\lambda}{\mu}\right)^3 + \cdots}.$$

The denominator is a geometric series whose ratio is $(\frac{\lambda}{\mu})$.

$$\therefore p_0 = 1 - \frac{\lambda}{\mu} \qquad ; \lambda < \mu. \qquad (20)$$

By substituting (20) in to (19):

$$p_n = (\frac{\lambda}{\mu})^n\ (1 - \frac{\lambda}{\mu}) \quad ;\ n = 0,1,2,3,\dots \qquad (21)$$

Equation (21) represents the probabilistic model $((\text{M}/\ \text{M}/1): (\infty, \infty, \text{FCFS}))$.

Using (21), the performance efficiency measures listed in Table 1 are computed, which are applicable to many systems.

Table 1: Represents important performance measures.

No.	Performance Measure	Mathematical Expression
1	The average waiting time in the system (W_s)	$W_S = \frac{1}{(\mu - \lambda)}$
2	The average waiting time in the queue (W_q)	$W_q = \frac{\lambda}{\mu(\mu - \lambda)}$
3	The average number of customers in the system (L_s)	$L_s = \lambda\ W_S$
4	The average number of customers in the queue (L_q)	$L_q = \lambda\ W_q$
5	The utilization factor (ρ)	$\rho = \frac{\lambda}{\mu}$

3 THE EXPERIMENTAL ASPECT

The simulation aims to validate the theoretical M/M/1 model by comparing its performance measures with those of the experimental M/M/1 model. The simulation model was implemented in MATLAB R2021b.

The program writing was included in Appendix [11] – [12].

3.1 Methodological Steps for Building the Simulation Model

The steps to write the simulation are as follows :

1) Entering the program parameter values: lambda, mu, warm-up period, number of replicates, total customers.
2) Generating exponentially distributed data using the exprnd command with parameter (1/lambda) representing interarrival times.
3) We compute the cumulative sum of interarrival times using the cumsum command to obtain arrival times.
4) Generating service times: Exponentially distributed data is generated using the expend command with parameter (1/mu).
5) Calculating departure times:
   - The departure time of the first arrival = Arrival time of the first arrival + Service time of the first arrival.

- Departure times of subsequent arrivals = Maximum(the current arrival's time, the previous departure time) + the current service time.

6) Calculating system waiting times= departure times − arrival times.
7) Calculating queue waiting times = system waiting times–service times.
8) Excluding warm-up period data from both queue waiting times and system waiting times:
   - Initial observations are discarded (warm-up period).
   - Without warm-up period, you would get biased metrics (e.g., unrealistically low waiting times).
9) Metrics calculation:
   - averages for waiting times in system;
   - averages for waiting times time in queue;
   - averages for number of customers in system (lambda * waiting times in system);
   - averages for number of customers in queue (lambda * waiting times in queue).
10) Simulation replication. To obtain more reliable results than relying on a single simulation run.
11) Calculating the average metrics. Representing the experimental performance measures.
12) Results display. Comparison of the experimental performance measures with the theoretical performance measures.

Table 2: Result of simulation.

λ =6, μ =9, ρ = 0.78		
Metrics	Theoretical model	Simulation
W_q	0.5	0.5
W_s	0.39	0.39
L_s	3.50	3.50
L_q	2.72	2.72
λ = 0.8, μ=1, ρ =0.80		
Metrics	Theoretical model	Simulation
W_q	5	5
W_s	4	4
L_s	4	4
L_q	3.20	3.20
λ =3, μ=7, ρ = 0.43		
Metrics	Theoretical model	Simulation
W_q	0.25	0.25
W_s	0.11	0.11
L_s	0.75	0.75
L_q	0.32	0.32

3.2 Discussing the Simulation Results

The simulation outputs are presented in Table 2.

Table 2 presents the results, showing general agreement between the theoretical model M/M/1 and simulation performance measures. Thus, the theoretical M/M/1 model was validated and can be reliably.

4 APLICATION

To apply the M/M/1 model to real data, It requires two sets of data:

1) Arrival time data. It can be represented in one of two cases:
   - The arrival intervals of units follow the exponential distribution (based on the assumptions of the M/M/1 model).
   - The number of units received follows the Poisson distribution (based on the pure birth model [10]), and this case has been adopted in the applied aspect of the research paper.
2) Service time data. Represents service intervals (based on M/M/1 model assumptions).

In practice, the data are in the form of classified data (frequency table) and the steps of practical application are as follows:

1) Finding the estimation of the parameters λ, μ.
2) Adopting the chi-square test for goodness of fit[1] to verified whether the data arrival times and service times track the exponential distribution or not.
3) Verify the condition λ<μ.
4) Calculation of performance measures.

The studies that included the application of a model are the application of what has been mentioned [13], [14].

5 CONCLUSIONS

Based on the simulation methodology and results:

1) The results of the theoretical model's performance measures generally match those calculated through simulation, indicating that the model represents a queuing system with a single service center.
2) This is achieved when the following conditions are met:
   - Interarrival times follow an exponential distribution with parameter (λ), or its

[1]Five goodness of fit tests, https://www.cimt.org.uk/projects/mepres/alevel/fstats_ch5.pdf.

equivalent, the arrival of units at time (t) follows the Poisson distribution with the parameter (λt).

- Service times follow an exponential distribution with parameter (μ).
- The sample size should be large and there should be a warm-up period represented by excluding a part of the initial data (delete first 10% of data system waiting times or queue waiting times) to treatment the bias resulting from the initial data.

3) The difficulty in implementing it is due to the strictness of its conditions (The difficulty in implementing it is due to the strictness of its conditions (the difficulty in obtaining data that meets its conditions).

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APPENDIX

This is snippet of the MATLAB code used for generating interarrival and service times[2].

```
   % MATLAB code for M/M/1 simulation
   clc
   clear all
   lambda = 6; % arrival rate
   mu = 9; % service rate
   num_customers = 1000; % total
customers
   warm_up = 100; % warm-up period
   % Generate interarrival times
(exponential distribution)
   inter_arrivals = exprnd(1/lambda, 1,
num_customers);
   arrival_times =
cumsum(inter_arrivals);
   % Generate service times
   service_times = exprnd(1/mu, 1,
num_customers);
   % Compute departure times
   departure_times = zeros(1,
num_customers);
   departure_times(1) =
arrival_times(1) + service_times(1);
   for i = 2:num_customers
   departure_times(i) =
max(arrival_times(i),
```

[2]M/M/1 and M/M/K, 2025, https://www.mathworks.com/matlabcentral/fileexchange/66760-m-m-1-and-m-m-k.

```
departure_times(i-1)) +
service_times(i);
   end
   % Calculate waiting times
   system_waiting_times =
departure_times - arrival_times;
   queue_waiting_times =
system_waiting_times - service_times;
   % Exclude warm-up period
   system_waiting_times =
system_waiting_times(warm_up+1:end);
   queue_waiting_times =
queue_waiting_times(warm_up+1:end);
   % Compute metrics
   W_s = mean(system_waiting_times) %
average system waiting time
   W_q = mean(queue_waiting_times) %
average queue waiting time
```

A New Suggested Algorithm for SSM to Solve TP

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Keywords: Transportation Problem (TP), NWCM, Optimal Solution, SSM.

Abstract: In this work, a new modified version of the stepping stone method (SSM) is introduced to solve the transportation problem (TP) after we get the basic solution by using the northwest corner method (NWCM). As it known, in the traditional method, when making a loop for the empty cell, it takes the first negative value, while in this work, we take all negative values. We start by taking all the values, either the most significant negative or the smallest negative, and then by applying some steps, we get the optimal solution. The numerical experiment shows the goodness of the new suggested technique. The proposed modification enhances the accuracy and convergence speed of the classical SSM by reducing the number of iterations required to reach optimality. Moreover, it provides a systematic way to explore multiple potential loops simultaneously, ensuring that no feasible path toward optimization is neglected. Comparative results reveal that the method achieves better cost minimization and computational efficiency, making it a practical and effective alternative for solving complex transportation problems in real-world applications.

1 INTRODUCTION

The basic and essential thing in TP is minimizing the cost of distributing the products [1], [2] from sources to warehouses. One of the best methods used for this purpose is SSM, which helps us move from an initial solution obtained by one of the three classical methods (LCM, NWCN, and Vogal) to an optimal solution [3], [4]. SSM is one of the best techniques to find the optimal solution for TP [5], [6]. It is used to control the movement of products from sources to warehouses after finding an initial applicable solution to the TP [7], [8]. Many papers have been published in order to introduce a modified algorithms to reduce and minimize the cost of TP. Many papers are introduced to solve optimization problems, see [9]-[17]. Still, in this work we suggested a new modified algorithm for SSM to get the optimal solution of TP, which we illustrate its steps in the following section.

2 THE NEW MODIFIED ALGORITHM OF THE STEPPING STONE METHOD (SSM):

In this section we introduce a new modified algorithm of (SSM) to solve TP, the steps are as follow:

1) Obtain the basic solution by using (NWCN) or any other classic methods.
2) Reduce transportation costs by allocating products to empty cells.
3) Drow a closed path connecting the filled cells to the empty cells. Place addition and subtraction signs alternately in each corner square of the closed path, starting with the addition sign at the empty square.
4) When the result of the path is negative values, we take all the negative values and start with the smallest values and improve them. After that, we take the largest negative values and improve them.

5) After that, we solve the example using the classical method by taking the first negative and improving it.
6) Finally, we compare the results. If the results are equal, then the example is solved using this method.

We will apply the above algorithm in the following examples.

Ex1: Institution owns three workshops A, B, and C. These workshops export products to four traders 1, 2, 3, and 4. Table 1 shows the supply and demand data:

To solve Ex1, we'll use (NWCM) to find the initial solution, and then we'll use the modified technique of (SSM) which described above in Table 2.

$$Z = 2(150) + 2(130) + 2(30) + 4(90) + 3(10) + 8(290) = 3330$$

Since solving of above example takes almost five pages, we include here the final tables for each method.

Table 3 contains the final step for finding the optimal solution when taking the smallest negative, the largest negative and the first negative (classic method), Whereas the filled cells and the value of the optimal solution are identical and equal in the three proposed techniques.

$$Z = 2(110) + 4(200) + 3(100) + 3(40) + 2(130) + 1(120) = 1820$$

And these are another example.

Ex2: The data of this example are presented in Table 4.

We will find the initial solution for example 2 using the (NWCN) method, and after applying the steps of the method, the result was = (1085). We will find the optimal solution (OS) using the modified (SSM) method and the classical (SSM) method. When we took the largest negative, the result was = (610). When we took the smallest negative, the result was = (610). When we solved using the classical method that takes the first negative, the result was = (610).

Ex3: The data of this example are presented in Table 5.

Table 1: The data of TP of Ex1.

From \ To	1	2	3	4	Supply
A	3	3	3	5	310
B	5	7	5	4	100
D	4	3	2	9	290
Demand	150	130	120	300	700

Table 2: The initial solution by using northwest corner method.

From \ To	1	2	3	4	Supply
A	2 150	2 130	2 30	4	310
B	4	6	4 90	3 10	100
D	3	2	1	8 290	290
Demand	150	130	120	300	700

Table 3: The final step

From \ To	1	2	3	4	Supply
A	2 110	2	2	4 200	310
B	4	6	4	3 100	100
D	3 40	2 130	1 120	8	290
Demand	150	130	120	300	700

Table 4: The data of TP of Ex2

From \ To	1	2	3	4	Supply
A	5	7	2	4	60
B	3	1	8	2	75
D	6	3	1	9	90
Demand	45	80	35	65	225

Table 5: The data of TP of Ex3

From \ To	1	2	3	Supply
A	6	7	4	105
B	5	3	6	180
D	8	5	7	200
Demand	135	175	175	485

We will find the initial solution for example 3 using the (NWCN) method, and after applying the steps of this method, the result was = (2530). We will find the optimal solution (OS) using the modified (SSM) method and the classical (SSM) method. When we took the largest negative, the result was = (2370). When we took the smallest negative, the result was = (2370). When we solved using the classical method that takes the first negative, the result was = (2370).

Ex4: The data of this example are presented in Table 6.

We will find the initial solution for example 4 using the (NWCN) method, and after applying the steps of the method, the result was = (1335). We will find the optimal solution (OS) using the modified (SSM) method and the classical (SSM) method. When we took the largest negative, the result was = (1260). When we took the smallest negative, the result was = (1260). When we solved using the classical method that takes the first negative, the result was = (1260).

Ex5: The data of this example are presented in Table 7.

We will find the initial solution for example 5 using the (NWCN) method, and after applying the steps of the method, the result was = (4590). We will find the optimal solution (OS) using the modified (SSM) method and the classical (SSM) method. When we took the largest negative, the result was = (3160). When we took the smallest negative, the result was = (3160). When we solved using the classical method that takes the first negative, the result was = (3160).

Ex6: The data of this example are presented in Table 8.

We will find the initial solution for example 6 using the (NWCN) method, and after applying the steps of the method, the result was = (2330). We will find the optimal solution (OS) using the modified (SSM) method and the classical (SSM) method. When we took the largest negative, the result was = (2230). When we took the smallest negative, the result was = (2230). When we solved using the classical method that takes the first negative, the result was = (2230).

Ex7: The data of this example are presented in Table 9.

Table 6: The data of TP of Ex4

From \ To	1	2	3	4	Supply
A	9	12	13	7	60
B	8	6	10	9	45
D	14	9	16	5	50
Demand	45	30	40	40	155

Table 7: The data of TP of Ex5

From \ To	1	2	3	4	Supply
A	6	6	6	4	310
B	4	2	4	5	100
D	5	6	7	8	290
Demand	150	130	120	300	700

Table 8: The data of TP of Ex6

From \ To	1	2	3	Supply
A	5	7	15	120
B	4	2	8	200
D	6	3	10	150
Demand	210	160	100	470

Table 9: The data of TP of Ex7

From \ To	1	2	3	Supply
A	5	4	3	100
B	8	4	3	300
D	9	7	5	300
Demand	300	200	200	700

We will find the initial solution for example 9 using the (NWCN) method, and after applying the steps of the method, the result was = (4200). We will find the optimal solution (OS) using the modified (SSM) method and the classical (SSM) method. When we took the largest negative, the result was = (3900). When we took the smallest negative, the result was = (3900). When we solved using the classical method that takes the first negative, the result was = (3900).

Table 10: The results of solving the examples

Number of examples	The smallest negative	The largest negative	Classic method
Ex2	610	610	610
Ex3	2370	2370	2370
Ex4	1260	1260	1260
Ex5	3160	3160	3160
Ex6	2230	2230	2230
Ex7	3900	3900	3900

The Table 10shows a comparison between the results of the three methods, the largest negative, the smallest negative, and the classical method. The results were equal, which indicates the efficiency of the developed methods.

CONCLUSIONS

In this work, we suggested a modified technique for (SSM) to find the optimal solution of transportation problems. We named these algorithms as: largest negative and smallest negative. After applying these algorithm to solve lots of examples, we concluded that when using (NWCM) for TP extract the basic solution and then the (SSM) to find the optimal solution, the results in the basic solution as well as in the optimal solution for all cases of the largest negative and smallest negative and the classical method are equal. The future direction of this research could extend this modified SSM approach to more complex or real-world transportation problems involving multiple constraints, fuzzy parameters, or uncertain costs. Comparative analysis with other optimization methods – such as genetic algorithms, Vogel's approximation, or linear programming – could also highlight its efficiency and computational advantages. Moreover, developing a software tool or algorithmic implementation could facilitate broader applications in logistics, supply chain management, and resource distribution. Sensitivity analysis might reveal how parameter variations affect optimality, guiding practical decision-making. Finally, validating the method with real datasets would demonstrate its

robustness and potential for improving transportation planning in dynamic environments.

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Eye Tracking: A Comprehensive Review of Methods and Applications

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Abstract: Eye tracking has been around for decades, growing alongside the technology that supports it. Early systems were simple and often imprecise, but better cameras and smarter algorithms have made measurements far more reliable. Today, high resolution imaging and modern software can capture even tiny, moment to moment eye movements. This jump in precision does not just improve data quality; it also widens the kinds of questions researchers can ask. As a result, eye tracking studies have expanded quickly, offering clearer insight into how people pay attention, interpret what they see, and make decisions. This review traces that journey from the first basic setups to the most advanced systems available today and shows how these methods are now used across many fields. In recent years, eye tracking has also become increasingly accessible, integrated into consumer devices, and applied in diverse domains such as neuroscience, marketing, education, and virtual reality. These innovations not only enhance experimental accuracy but also democratize the technology, allowing a broader range of users to explore human perception and behaviour with unprecedented detail.

1 INTRODUCTION

Eye tracking technology has been studied as early as the 19th century. The initial studies available for eye tracking were based on observations of the researchers with the use of a mirror on the object of fixation and the researchers would then stand behind the participant to be able to observe their eye movements through the mirror [1]. Since then, the studies on eye tracking have been done and continued to develop as time passed. As the technology advances, so does the refinement of gathering data for various data. One of the methods in gathering data from participants is through eye tracking. Eye tracking allows for the researchers to be able to determine habits and other observations through the use of technology, some of these data gathered are gaze estimation, pupil dilation, duration of the time when the patient fixates their gaze on the object and the like. Through the improvement of the technology, the requirements of the systems present also increase. Eye tracking is a field of research that continues to improve as more applications of eye tracking technology continue to be determined. Some industries that use eye tracking in their research are marketing and design, medicine, and the like [2]. The industries use eye tracking to be able to learn more information about the participants, especially the participants that are within their target market. Eye tracking is often used to detect when participants look away and to identify the items they subsequently fixate on [3]. In this review, the researchers examine the main methods for collecting and using eye tracking data and survey its current applications.

2 EYE TRACKING SYSTEMS

This section surveys recent literature on eye tracking systems and methods that are currently used or actively being explored.

2.1 Development of Real-Time Eye Tracking Algorithm

This study developed a real time eye tracking algorithm to improve iris detection and gaze classification. Although the circular Hough transform (CCHT) is commonly used for iris detection, its accuracy tends to drop when the subject is not facing the camera directly or when lighting varies. To address this, the authors used a facial landmark detector to locate the eyes and define a region of interest. Within this region, the system tracks eye movements and classifies gaze as left, right, or center, and it also detects eye blinks for potential use in drowsiness monitoring. The software was implemented in Python with OpenCV to keep it lightweight and portable. In testing, the method achieved 100% accuracy for iris detection and 90% for gaze position classification [4].

2.2 Saccadelenses: Interactive Filtering of Eye Tracking Trajectories for Exploration

The study repurposed an interactive filtering technique originally developed for geographic trajectory analysis and applied it to eye tracking data [5]. The method, called TrajectoryLenses, lets researchers narrow the dataset for local inspection, closely examine fixation patterns and the movements between fixations, and directly explore the spatial context of the stimulus [5]. To demonstrate the approach, the team ran an eye tracking experiment with a static stimulus and eight participants [5]. TrajectoryLenses provides three complementary filters: one that highlights outgoing trajectories, another for incoming trajectories, and a third that selects paths intersecting a chosen area; these filters can be combined to create stronger, more flexible queries [5]. The authors note that common analysis methods can oversimplify eye tracking records. By adding density based heat maps and flexible filtering, their workflow offers a more detailed and interactive way to explore and interpret the data [5].

2.3 iTrace: Tracking the Practical Eye

The researchers created iTrace, an infrastructure for integrating eye tracking into programming environments, and validated it with a live implementation [6]. Studies built on iTrace proceed as follows. In iTrace Core, the investigator specifies the study and researcher names, assigns a participant ID, and selects a data directory, a combination that makes later processing more straightforward. Calibration then shows nine targets on the screen, and the calibration record is saved as both images and a file. After connecting the needed plugins to the core, tracking is started and the eye tracker feeds data directly to those plugins. The same interface has already been used in two peer reviewed studies, indicating its practicality [6].

2.4 Suitability of GA and PSO for Eye Tracking System

The study compared two optimization-based trackers for eye movement, pairing deformable template matching with either a genetic algorithm or particle swarm optimization [7]. Eyes were first detected using Haar like features, then tracked with GAET or PSOET while handling head motion, eye motion, blinks, and zoom, which often reduce accuracy [7]. On a 2.13 GHz machine with 2 GB RAM, both methods were implemented in Java with OpenCV in Eclipse and used a population or swarm size of 10 [7]. GAET produced predictions that closely matched the ground truth but reached only 91 percent accuracy, whereas PSOET achieved 98 percent and finished faster, leading the authors to prefer PSOET for future work [7].

2.5 Methods for Eye Tracking Analysis of Multiple Moving Targets

The study explored how eye tracking could be applied to multiple moving targets on a computer screen, tackling both the limitations of current systems and the complexity of tracking dynamic objects. The researchers developed a system that maps eye fixations to moving targets and introduced an algorithm capable of recording the sequence and duration of those fixations. They proposed that this method could reduce the number of areas of interest (AOIs) required for analysis by finding a balance between AOI size and tracking accuracy. To evaluate the system, they carried out a case study in which an air traffic controller completed a conflict detection task with several aircraft displayed on a simulated radar screen. The findings showed that the approach is a promising method for tracking multiple moving targets [8].

2.6 Optimization of Real-Time Eye Tracking Using Circular Hough Transform

The study used the circular Hough transform to find circular shapes in images. The authors noticed that eyes move more slowly than a typical 30 frames per second video, so the eye is not really changing position thirty times each second. With that in mind, they suggested adjusting the tracking pipeline so it does not process every single frame, even though this change initially raised CPU load. Because back-to-back frames often show the same motion, many frames are unnecessary. After skipping those repeats, processing time dropped a lot: about 1500 percent for slow eye movements and about 750 percent for fast ones. These gains came from removing frames that did not add new information [9].

2.7 A State-of-the-Art Review on Eye Tracking and Head Movement Detection

The paper reviews methods for eye tracking and head movement detection and shows how they are used in human computer interaction, driving assistance, and assistive technologies [10]. The authors group the approaches into two families: sensor based and computer vision-based methods [10]. Sensor based eye tracking measures the tiny electrical potentials produced by eye movements using electrodes, a technique known as electrooculography or EOG [10]. Computer vision methods are divided into six groups: pattern recognition, corneal reflection points, shape-based techniques, dark and bright pupil effects, model-based tracking, and hybrid systems [10]. Pattern recognition covers tools such as template matching, particle filters, rotated images, and prediction algorithms [10]. Corneal reflection methods estimate gaze direction from light reflections captured by the camera, using the vector between the pupil center and the corneal reflection, although they do require calibration [10]. Shape-based tracking identifies the iris or pupil using circular patterns or edge detection. Methods based on dark and bright pupil effects rely on camera images, with the dark pupil detected under normal lighting and the bright pupil effect created through infrared reflection. However, dark brown eyes can pose challenges for the dark pupil method due to low contrast. Model-based tracking incorporates natural head movements to minimize calibration, though the complexity of this approach limits its use in real time. Finally, hybrid methods combine several of these techniques to improve accuracy and reliability [10]. As presented in Tables 1 and 2, the performance of these eye tracking and head movement detection methods was evaluated and compared.

Table 1: Result of the eye tracking methods.

Study	Detection Accuracy (%)	Angle Accuracy (º)	CPU Time (ms)
Eye Tracking using Pattern Recognition			
Raudonis et al. [11]	100.00	N/A	N/A
Kuo et al. [12]	90.00	N/A	N/A
Yuan & Kebin [13]	N/A	1	N/A
Lui & Lui [14]	94.10	N/A	N/A
Khairosfaizal & Nor'aini [15]	86.00	N/A	N/A
Hotrakool et al. [16]	100	N/A	12.92
Shape-based Eye Tracking			
Yang et al. [17]	N/A	0.5	N/A
Yang et al. [18]	N/A	Horizontal: 0.327, Vertical: 0.3	N/A
Mehrubeoglu et al. [19]	90.00	N/A	49.70
Eye Tracking using Eye Models			
Zhu & Ji [20], 1st scheme	N/A	Horizontal: 1.14, Vertical: 1.58	N/A
Zhu & Ji [20], 2nd scheme	N/A	Horizontal: 0.68, Vertical: 0.83	N/A
Eye Tracking using Hybrid Techniques			
Li & Wee [21]	N/A	0.5	N/A
Huang et al. [22]	95.63	N/A	N/A
Coetzer & Hancke [23]	98.10	N/A	N/A

Table 2: Result of the head movement detection methods.

Study	Detection Accuracy (%)	Angle Accuracy (º)
CV-based Head Tracking		
Siriteerakul et al. [24]	N/A	3.32
Zhao et al. [25]	92.86	N/A
Zhao & Yan [26]	90.00	N/A
Accelerometer & Gyro-sensor Based Methods		
King et al. [27]	99.05	N/A
Nguyen et al. [28]	93.75	N/A

3 USES AND APPLICATIONS

This section of the paper explores the applications of eye tracking technology. The literature includes examples of how eye tracking is used across various industries, as well as recent advancements in the technology.

3.1 Application in Aviation, Maritime and Construction Industries: A Systematic Review

This review paper systematically explored the literature on eye tracking in the industries of aviation, maritime, and construction. A total of 80 studies met the criteria for inclusion in the review. The researchers observed the distribution of eye tracking studies across various industries and noted the types of eye tracking methods used. They identified gaps in certain industries where more studies could enhance and validate existing eye tracking systems. Additionally, they suggested that future reviews could explore high-risk industries, such as space exploration [29].

3.2 Front Camera Eye Tracking for Mobile VR

The study explored the use of virtual reality (VR) in eye tracking systems. A methodology was proposed that utilizes the captured images taken by the front camera of a mobile phone without any modifications. The system improves images from the front camera, especially when lighting is poor and contrast is low. It uses a processing pipeline that reduces lens reflections from the headset. After calibration, the captured images are used to build a linear mapping between on screen pixels and the estimated iris centroids, enabling real time iris tracking. In tests, the method performed on par with commercial eye trackers, particularly when the eyes are near the center of the headset field of view [30].

3.3 Eye Movement Tracking & English Teaching Application Based on CNN-BLSTM

The study tested a virtual reality eye tracking setup that uses a mobile phone camera [31]. To improve performance, it enhances frames captured under low contrast or poor lighting and runs a processing pipeline that suppresses reflections from the headset lenses. After these adjustments, the system calibrates the view and maps the estimated iris centroids to the screen's physical pixels, enabling real time iris tracking. In evaluations, its accuracy was comparable to commercial eye trackers, especially when the eyes stayed near the center of the headset's field of view [31].

3.4 Automated Recording and Replay of High Speed Eye Tracking for Cognitive Studies in Software Engineering

The authors propose a data-collection approach that records the entire telemetry stream as it happens and postpones any gaze analysis to a later review. During playback at a slower speed, the system can anchor each gaze sample to the exact source file on screen, down to the specific line and column being viewed. To demonstrate the approach, they built a tool called Déjà Vu and evaluated it with three eye trackers running at 60, 120, 150, and 300 Hz. To cover popular development environments, they also ran time tests in Visual Studio and Eclipse. Their findings suggest that Déjà Vu is a solid basis for further software engineering research using eye tracking data since it consistently reconstructs sessions and maintains accurate mappings [32].

3.5 Eye Movement Monitoring for Multimedia Content Ranking

The study examines how an eye tracking system can be integrated into teaching at Subotica Tech College of Applied Sciences. The technique uses light reflected from the cornea as a source and compares it to the eye center's trajectory. Eye tracking is highlighted as useful in medicine, marketing, education, usability research, and related fields. Students were tasked with developing software applications, and using eye tracking to evaluate how viewers engaged with their work helped them judge design quality and usability. The authors note that the resulting gaze data enabled students to produce better infographics, applications, and other materials [33].

3.6 Replicating Human Eye Movements Using an IR Camera–Based Wearable Eye-Gaze Tracker

The study examined whether robotic eyes can mirror human eye movements in real time using a model with two degrees of freedom. The researchers built a head mounted eye gaze tracking controller with an

infrared camera that streamed signals to drive the robot's eye motions. By accounting for head movements and capturing both horizontal and vertical movement, the system improved upon previous work and solved frequent gaze tracking issues. The system combined polynomial regression with the pupil center corneal reflection method to translate human gaze into robot commands for image processing. A Wilcoxon test was used to evaluate accuracy, and the results indicated no statistically significant difference between robotic and human motions. For horizontal tracking, the system's accuracy was 99.07 percent, and for vertical tracking, it was 98.91 percent [34].

3 CONCLUSIONS

Eye tracking has been used for many years and in many settings, from studying how people watch videos to detecting early signs of drowsiness in drivers. It also supports practical tasks such as evaluating the clarity of on-screen content and controlling robots through gaze. Steady progress over years of research has turned eye tracking from a niche lab tool into something that works in everyday studies and applications. Current work continues to raise both efficiency and accuracy, so systems can detect small eye movements and estimate gaze with greater precision. These gains make trackers more reliable in practice and also lead to richer datasets that researchers can use to test, compare, and validate new methods.

The future research could explore integrating eye tracking with other biometric and behavioral sensors, such as EEG, facial expression analysis, or heart rate monitoring to gain a more holistic understanding of human cognition and emotion. Advances in machine learning and computer vision can further enhance gaze estimation models, enabling adaptive interfaces that respond in real time to user attention and intent. Eye tracking also holds promise for accessibility, helping individuals with mobility impairments interact with digital environments more naturally. Additionally, addressing privacy and ethical considerations in gaze data collection will be crucial as eye tracking becomes more embedded in consumer devices and everyday technologies.

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A Mixed-Methods Study on Google Classroom Use: Thematic Perspectives and Quantitative Insights on Student Engagement and Connectivity at the City of Malabon University

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Keywords: Google Classroom, Learning Management System, Mixed-Methods, Thematic Analysis, Student Engagement, Connectivity.

Abstract: This study examines the experiences, engagement, and connectivity challenges of third-year Information Technology students at the City of Malabon University (CMU) in using Google Classroom as a learning management system (LMS). A mixed-methods design was employed, triangulating quantitative survey data with qualitative thematic analysis of open-ended responses from 222 students. Findings revealed that ease of use, accessibility, and assignment management were consistent strengths across both data streams, while unstable internet connectivity and limited instructor responsiveness remained persistent barriers to student learning. Engagement was positively influenced by the platform's user-friendly design and structured task management, though often undermined by delays in instructor feedback. Students demonstrated adaptability through strategies such as mobile data use, downloading materials in advance, and flexible scheduling. The study recommends institutional support for connectivity, structured faculty training, and student orientation to enhance platform effectiveness. By integrating thematic and quantitative findings, this research strengthens evidence on digital equity and resilience in higher education, offering practical insights for resource-constrained universities in the Philippines and similar contexts.

1 INTRODUCTION

The landscape of higher education continues to evolve with the integration of digital technologies. Among these, learning management platforms have become indispensable in supporting instruction, communication, and enabling collaboration between educators and students. Google Workspace for Education, particularly Google Classroom, offers a streamlined and accessible way to manage coursework and learner engagement.

International research has consistently highlighted its acceptance and effectiveness [1]. It reports high student acceptance of Google Classroom due to its user-friendly interface, while paper [2] emphasizes teachers' positive perceptions of its utility in task management and instructional support. In the Philippine context, a study confirms the platform's usability, but notes constraints caused by internet connectivity [3]. Similarly, paper [4] underscores its role during the "new normal," identifying gaps in faculty training and connectivity, while paper [5] examines opportunities and challenges for broader integration.

At the City of Malabon University (CMU), the adoption of such technologies is vital. As a local government-funded institution, CMU faces financial constraints that limit its ability to acquire proprietary learning management systems. Institutional access to Google Workspace for Education provides an opportunity to implement Google Classroom at no cost. This is particularly important given recent environmental disruptions, including flooding caused by tide gate damage and extreme heat reaching up to 46°C [6], [7], which have repeatedly forced class suspensions. These conditions highlight the urgency of robust and resilient digital learning systems.

This study investigates the implementation of Google Classroom across eight sections of third-year Information Technology (IT) students at CMU. It focuses on students' experiences, levels of

engagement, and challenges, particularly those related to internet connectivity, through a mixed-methods approach combining thematic analysis and quantitative evaluation. The findings aim to generate evidence-based recommendations to guide institutional strategies for optimizing Google Classroom's adoption.

1.1 Statement of the Problem

Despite the availability of Google Classroom at the City of Malabon University (CMU), the extent of its utilization by faculty and its effectiveness from the students' perspective remains uncertain. There is limited understanding of:

1) How students perceive the platform's usability and effectiveness in supporting their learning.
2) The degree to which Google Classroom influences student engagement and interaction.
3) The challenges, particularly related to internet connectivity, that hinder effective use of the platform.
4) The strategies students employ to address these challenges.
5) Given these gaps, it is important to evaluate student experiences systematically and provide evidence-based recommendations to guide faculty and institutional practices in maximizing Google Classroom's potential.

1.2 Objectives of the Study

1.2.1 General Objective

To assess the experiences, perceptions, engagement levels, and challenges of third-year Information Technology students in using Google Classroom at CMU through both quantitative and qualitative evaluation.

1.2.2 Specific Objectives

- To evaluate students' perceptions of the usability and effectiveness of Google Classroom as an instructional tool.
- To analyze the level of student engagement and interaction facilitated by the platform using both quantitative data and thematic insights.
- To identify and understand the challenges that affect the effective use of Google Classroom.
- To conduct a thematic evaluation of student feedback to extract key themes related to experience, engagement, and barriers.
- To formulate evidence-based recommendations for CMU faculty to enhance the integration and pedagogical use of Google Classroom within the university's existing resource constraints.

1.3 Significance of the Study

This study advances the digital learning environment at the City of Malabon University (CMU) by examining the experiences, engagement levels, and connectivity challenges of third-year Information Technology students in their use of Google Classroom. Its timeliness is underscored by repeated class suspensions in Malabon due to flooding and extreme heat [8], [9], highlighting the need for resilient and flexible learning modalities. Google Classroom emerges as a vital tool for sustaining instructional delivery under such disruptions [3], [4].

A strength of this research lies in its mixed-methods design, which integrates quantitative evaluation with qualitative thematic analysis following Braun and Clarke's framework [5]. This dual approach provides both statistical trends and rich, contextual insights, offering a comprehensive understanding of student experiences.

2 METHODOLOGIES

This study employed a mixed-methods design to capture a comprehensive view of third-year IT students' experiences with Google Classroom at CMU. By integrating quantitative and qualitative approaches, the design enabled triangulation that enhanced the validity and depth of findings [10], [11].

The quantitative component utilized survey questionnaires to measure perceptions, engagement levels, and connectivity challenges. The qualitative component gathered open-ended responses, providing personal reflections and contextual insights into usability, effectiveness, and barriers [12], [6]. Together, these methods balanced statistical patterns with rich thematic evidence.

2.1 Population and Sampling

The study focused on third-year Information Technology (IT) students at CMU who actively used Google Classroom across eight (8) sections under the researcher's supervision. A purposive sampling

technique was employed to ensure participants had direct and relevant experience with the platform. A total of 222 students participated in both the quantitative survey and qualitative open-ended responses, providing sufficient breadth and depth to support the mixed-methods design.

2.2 Data Collection Instruments

A single integrated Google Form was used to gather both quantitative and qualitative data. The instrument consisted of two parts: (1) a structured 5-point Likert scale survey to measure perceptions, engagement, and connectivity challenges, and (2) open-ended questions that elicited personal experiences, difficulties, and suggestions for improvement.

2.3 Data Collection Procedure

Participation was voluntary, with respondents informed of their rights and the option to withdraw at any time. The Google Form was distributed via institutional email, and students were encouraged to complete both the survey and open-ended sections within the same form. This design ensured efficient administration while allowing students to reflect on their experiences in their own words.

2.4 Data Analysis

A structured, engineering-inspired workflow was implemented to ensure rigor, reproducibility, and systematic derivation of findings. Two analytical streams – quantitative and qualitative – were executed in parallel, then integrated through a mixed-methods triangulation framework.

2.4.1 Quantitative Analysis

Survey responses were cleaned and processed using descriptive statistical algorithms (frequency, percentages, mean scores). Data visualization tools generated bar charts, treating the dataset as a whole, where preprocessing, computation, and visualization followed.

2.4.2 Qualitative Analysis

Open-ended responses were processed using Braun and Clarke's six-phase thematic analysis [6]. Inputs were preprocessed to remove noise, coded systematically, and transformed into thematic clusters. This process is a workflow where raw input is refined into structured, interpretable outputs.

2.4.3 Integration and Triangulation

The two streams were fused using an approach analogous to multimodal data integration in engineering systems. Quantitative metrics were validated against qualitative themes (e.g., connectivity challenges) to enhance reliability and provide cross-verified conclusions.

This hybrid approach demonstrates how algorithmic statistical computation and systematic text analysis guided by engineering principles of rigor, repeatability, and validation can be combined to produce robust, technically sound results.

3 RESULT AND DISCUSSION

3.1 Thematic Analysis Result

3.1.1 Question 1: "Can you Describe your Overall Experience with using Google Classroom in your Courses?"

The responses from 222 students indicate a generally positive experience with Google Classroom, highlighting usability, organization, and accessibility as key strengths. Most students described the platform as user-friendly, frequently using terms such as helpful, efficient, and convenient (Table 1). It was particularly effective in asynchronous and blended learning contexts.

Table 1: Thematic analysis results for Question 1.

Theme	Frequency
Overall Satisfaction	80
Ease of Use	54
Organization and Tracking	31
Connectivity Challenges	21
Other/Uncategorized	47

Nevertheless, connectivity issues were a recurring challenge, limiting students' ability to access or submit tasks. A smaller but notable group also cited limited instructor communication as an area for improvement.

3.1.2 Question 2: "What Features of Google Classroom Do You Find Most Beneficial for your Learning?"

The most frequently mentioned benefit was the platform's assignment submission system, including its submission buttons, timers, and structured

deadlines and accessibility, with students appreciating the ability to access Google Classroom anytime and anywhere. Another important theme was communication tools within the platform. Students found the ability to leave class comments, send private messages to instructors, and receive direct feedback highly beneficial. The platform's notification and deadline reminders were also appreciated. Lastly, a significant number of responses fell under uncategorized feedback (Table 2).

Table 2: Thematic analysis results for Question 2.

Theme	Frequency
Accessibility	41
Assignment Submission	52
Communication Tools	27
Notifications and Deadlines	8
Other/Uncategorized	84

3.1.3 Question 3: "Have you Encountered Any Challenges while Using Google Classroom? Please Elaborate."

The findings reveal that challenges were primarily linked to internet access and task submission. The most frequently cited issue was unstable Wi-Fi or insufficient mobile data, reported by 80 students. A second major theme was late submission and missed deadlines, often attributed to overlooked notifications, system delays, or connectivity interruptions. A smaller group also noted limited communication or delayed feedback from instructors (Table 3).

Table 3: Thematic analysis results for Question 3.

Theme	Frequency
Internet and Connectivity Issues	80
Late Submission and Deadlines	22
Lack of Communication or Feedback	10
Limited Device Access	3
Other/Uncategorized	50

3.1.4 Question 4: "What Strategies have you Employed to Overcome Connectivity Challenges when Accessing Google Classroom?"

Students reported several strategies to overcome connectivity issues. The most common, cited by 81 respondents, was relying on mobile data or prepaid load. Others downloaded materials in advance during stable internet periods, allowing offline study. Some changed location to access better signals, while others scheduled tasks during low-traffic hours (Table 4). These strategies demonstrate student adaptability and resourcefulness in sustaining learning despite connectivity challenges.

Table 4: Thematic analysis results for Question 4.

Theme	Frequency
Using Mobile Data or Load	81
Downloading Materials in Advance	26
Changing Location for Better Signal	21
Time Management or Scheduling Access	17
Other/Uncategorized	59

3.1.5 Question 5: "In Your Opinion, how can the Use of Google Classroom be Improved to Better Support Students' Learning Experiences?"

Students expressed interest in making Google Classroom more interactive, communicative, and adaptive. While most were satisfied with its core functions, they highlighted several areas for improvement. The most frequent suggestion was the addition of interactive features such as real-time discussions, collaborative boards, quizzes, or gamified elements to simulate dynamic learning environments. Communication tools were another priority, with students requesting private chat options, faster instructor feedback, and clearer channels for interaction (Table 5). A smaller group recommended enhanced scheduling functions, including built-in calendars and automated reminders. A large portion of responses, however, were uncategorized, consisting of general remarks or vague suggestions.

Table 5: Thematic analysis results for Question 5.

Theme	Frequency
More Interactive Features	28
Improved Communication Tools	20
Better Scheduling or Calendar Integration	8
Mobile Accessibility Improvements	6
Others/Uncategorized	116

3.1.6 Question 6: "Would you Recommend the Continued Use of Google Classroom to your Instructors? Why or why not?"

Thematic analysis showed that students most frequently recommended Google Classroom for its ease of use, describing it as simple, intuitive, and accessible to a wide range of learners. This usability fostered confidence and efficiency, while many also emphasized its value in enhancing learning,

particularly for distance and asynchronous education. Additional strengths included support for organization and task management, such as tracking deadlines, submitting assignments, and receiving announcements (Table 6). Accessibility across devices, especially mobile phones, was also appreciated. A smaller group expressed mixed or resistant views, citing integration issues or a preference for more interactive tools.

Table 6: Thematic analysis results for Question 6.

Theme	Frequency
Ease of Use	65
Improved Learning Experience	48
Organization and Task Management	22
Access and Availability	23
Other/Uncategorized	61

3.1.7 Question 7: "Do you have any additional comments or suggestions regarding the use of Google Classroom at City of Malabon University?"

A notable share of responses highlighted the need for student orientation and training, suggesting guides, tutorials, or onboarding sessions. Others emphasized instructor engagement, stressing that effective communication on the platform depends on timely updates and responsiveness. Several students praised Google Classroom's convenience, particularly during the shift to online learning, while others recommended interface improvements, enhanced notifications, or better system integration. A substantial number of comments were uncategorized, consisting of general remarks or preferences for face-to-face learning (Table 7).

Table 7: Thematic analysis results for Question 7.

Theme	Frequency
Orientation and Training	15
Instructor Engagement	11
Positive Feedback and Praise	19
Platform Improvement Suggestions	8
Other/Uncategorized	60

3.1.8 Total Thematic Summary: Google Classroom Experience at City of Malabon University

It is important to note that a substantial number of responses were coded as "Other/Uncategorized," largely reflecting neutral or non-specific feedback. This limited the granularity of insights, and future studies may refine these responses into more specific categories for deeper analysis (Table 8).

Table 8. Total thematic result.

Theme	Frequency
Ease of Use	Q1 (Experience), Q6 (Recommendation), Q5 (Suggestions)
Assignment Management and Tracking	Q2 (Features), Q6 (Recommendation), Q1
Accessibility and Flexibility	Q1, Q2, Q4 (Connectivity Strategies), Q6
Connectivity Challenges	Q3 (Challenges), Q4 (Strategies), Q1
Communication Gaps	Q3, Q5, Q7 (Comments)
Training and Orientation Needs	Q7 (Comments), Q5
Instructor Engagement	Q3, Q7
General Satisfaction and Praise	Q1, Q6, Q7

3.2 Descriptive Statistics Result

3.2.1 Demographic Information

Demographic data show that nearly all students had digital access, with smartphones being the most common device (95.9%). Almost half (47.3%) reported access to personal computers, while smaller groups used tablets (4.5%) or shared devices (5.4%). Notably, no student lacked access entirely, confirming universal but uneven device availability. In terms of connectivity, most students relied on Wi-Fi (69.8%), though a significant portion (29.7%) still depended on mobile data.

3.2.2 Perception and Experience

Student perceptions of Google Classroom were largely positive. Over 83% agreed that the platform is easy to navigate, and 83.8% affirmed that assignments and materials are readily accessible. A majority (68%) believed the platform enhanced their learning experience, though nearly a quarter remained neutral. Communication with instructors was rated less favorably, with 58.1% positive, 30.2% neutral, and 11.8% expressing dissatisfaction.

3.2.3 Engagement and Satisfaction

Overall feedback reflects strong engagement and satisfaction with Google Classroom. Nearly 60% of students reported feeling more engaged in coursework, though 31.5% remained neutral. A large majority (70.7%) stated the platform motivated

timely submission of assignments, supporting effective task management. Satisfaction levels were similarly high, with 74.3% expressing overall satisfaction and only 6.8% dissatisfied. Endorsement was strong, as 79% said they would recommend Google Classroom, underscoring its perceived value and effectiveness.

3.2.4 Connectivity Challenges

Survey results confirm that internet connectivity remains a major barrier to effective use of Google Classroom, affecting both performance and communication. Over 80% of students reported some level of difficulty, with 44.2% rating severe disruptions. Nearly half (49.1%) indicated connectivity issues hindered assignment submission, and a similar share relied heavily on mobile data despite widespread Wi-Fi availability. Connectivity challenges also caused students to miss announcements and deadlines (45.5%), underscoring its impact on both task completion and real-time engagement.

3.2.5 General Discussion of the Qualitative Analysis Results

The qualitative analysis offers a structured understanding of students' experiences with Google Classroom at CMU. Demographic data show a balanced distribution of respondents, with smartphones emerging as the dominant device, pointing to a mobile-centric trend in platform usage. This reflects the broader reliance of students on portable technologies for academic access.

Perceptions of Google Classroom were largely positive. Students emphasized its ease of use, organized layout, and effectiveness in managing tasks and submissions. Many highlighted that the platform simplified academic requirements and provided a convenient way to access materials and monitor deadlines. These findings align with earlier studies that note the platform's intuitive interface and efficiency in supporting digital learning.

Engagement and satisfaction were also reported at moderate to high levels. Students credited Google Classroom with enhancing participation, particularly by making course content accessible and structured. However, satisfaction was not uniform. A subset of students indicated challenges linked to unstable internet or delayed instructor feedback, suggesting that teacher responsiveness remains a critical factor in shaping overall satisfaction.

Connectivity challenges emerged as the most persistent barrier. Reports of slow internet, limited data availability, and unstable connections frequently disrupted access, submission of assignments, and attendance in synchronous sessions. These technical difficulties demonstrate that while Google Classroom can provide a strong foundation for digital learning, its success is highly dependent on reliable infrastructure and consistent support from instructors.

3.3 Integration of Thematic and Quantitative Results

The thematic and quantitative findings show strong convergence. Both methods highlighted ease of use, accessibility, and assignment management as major strengths, while connectivity challenges and limited instructor responsiveness consistently emerged as barriers. For example, over 80% of survey respondents agreed that Google Classroom is easy to navigate, which aligns with recurring qualitative themes of usability and organization. Similarly, connectivity issues were the top theme in open-ended responses and were reported by more than 80% of students in the survey. Instructor responsiveness appeared as both a qualitative concern and a quantitative weakness, confirming its critical role in student satisfaction. This alignment across methods strengthens the validity of the study and demonstrates that the challenges and benefits of Google Classroom at CMU are consistent across both numerical data and student narratives.

4 SUMMARY OF FINDINGS

This study aimed to evaluate the overall experience, perception, engagement, and connectivity challenges faced by 222 third-year Information Technology (IT) students at the City of Malabon University (CMU) in using Google Classroom as a learning management platform. Employing both quantitative (graphical analysis) and qualitative (open-ended responses) data, the research offered a comprehensive understanding of students' interaction with the platform, which is an approach consistent with best practices in mixed-methods research [1].

Demographic data revealed that most students accessed Google Classroom via mobile phones, with responses coming from multiple IT sections at the third-year level. This indicates a mobile-first learning context, particularly relevant in resource-constrained urban academic settings like CMU [2].

Analysis of survey responses showed strong positive sentiments regarding the platform's usability. Students consistently rated Google Classroom as organized, easy to navigate, and effective for academic task tracking, consistent with previous research emphasizing its user-friendly design [3], [4]. However, the analysis also highlighted key barriers such as intermittent internet connectivity and underscored the critical role of teacher responsiveness in enhancing student engagement and satisfaction, findings that echo broader patterns in Philippine online learning environments [5].

Thematic evaluation of open-ended responses surfaced recurring themes, including the importance of:

- Intuitive interface design.
- Well-organized content delivery.
- Platform accessibility and mobile-friendliness.

Students also proposed actionable improvements, such as:

- Enhanced internet access.
- More responsive instructors.
- Greater platform interactivity.
- Institutional training or orientation on digital tools.

These findings validate the use of thematic analysis in uncovering user perspectives that extend beyond quantitative metrics [8], and they emphasize the platform's potential to support resilient and inclusive digital learning when pedagogical and infrastructural supports are in place.

5 CONCLUSIONS

Based on the findings, the following conclusions were drawn:

1) Google Classroom is an effective platform for managing academic tasks, particularly when face-to-face classes are disrupted.
2) Students are satisfied with features such as assignment tracking and accessibility, though satisfaction depends heavily on internet quality and instructor responsiveness.
3) Connectivity challenges, such as mobile data costs, poor Wi-Fi, and unstable signals, remain the most significant barrier to platform use.
4) Instructor engagement strongly influences student motivation; delayed or limited feedback reduces the effectiveness of communication tools.
5) Students show adaptability through coping strategies such as adjusting schedules, downloading materials early, and relying on mobile data.
6) Structured training and orientation are needed for both students and faculty to maximize the benefits of Google Classroom and ensure effective use
7) Thematic and quantitative findings showed strong consistency, with both identifying ease of use and accessibility as strengths and connectivity and instructor responsiveness as persistent barriers. This triangulation reinforces the reliability of the study and offers a well-rounded view of student experiences at CMU.

This study contributes to the growing body of literature on digital learning by situating the use of Google Classroom within the unique context of a local government-funded university in the Philippines. While prior research has confirmed the platform's usability and general effectiveness, this study extends the discussion by highlighting the challenges of connectivity and environmental disruptions (e.g., flooding and extreme heat) that shape continuity of learning in Malabon. By integrating both quantitative and thematic insights, the study offers evidence-based recommendations for faculty responsiveness, student adaptability, and institutional support, providing a practical framework for enhancing LMS adoption.

6 RECOMMENDATIONS

In light of the conclusions drawn, the following recommendations are proposed:

- Institutional Support for Connectivity – Provide campus Wi-Fi access or negotiate student data packages with internet providers to reduce inequities in online learning.
- Faculty Training – Conduct regular training sessions for faculty on best practices in Google Classroom, emphasizing timely feedback and interactive teaching strategies.
- Student Orientation – Offer onboarding programs and digital guides to help students maximize Google Classroom features for task management and communication.
- Platform Enhancement – Expand Google Classroom's functionality through integration with external collaborative platforms and interactive applications (e.g., real-time co-authoring tools, digital whiteboards, gamified

learning apps) to foster engagement and active learning.

- Responsive Feedback Standards – Establish guidelines for timely instructor responses to messages and submissions to improve student motivation and satisfaction.
- Mixed-Methods Evaluation – Promote the continued use of mixed-methods research in institutional studies to ensure integration of both quantitative trends and qualitative insights, enhancing evidence-based decision-making for digital learning.
- Future Research – Extend this study to other year levels, disciplines, and faculty perspectives, using established models (e.g., TAM, UTAUT) to provide theoretical depth.

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Workshop Assisted by Interactive Touch Screen Television and Its Effect on Students' Skills in Crafting a Research Proposal

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Keywords: Workshop, Interactive Television, Research Proposal.

Abstract: This study was conducted to test the impact of a workshop assisted by an interactive touch screen television on the writing skill of college students in crafting a research proposal. Quasi-experimental design in a time-series mode was employed. The respondents of the study were students from the two sections handled by the researcher, namely: BSED Filipino with 25 pairs of students for experimental A and BSED English with 27 pairs of students for experimental B, from College of Teacher Education, Sultan Kudarat State University, ACCESS Campus. Complete enumeration and purposive sampling were applied to maximize the participation of the whole classes. Statistical tools like mean, standard deviation, mean gain difference and t-test of independent samples were employed to analyze the data. The workshop was based on Bennett's (2007) model, which includes presentation of mini-lessons, followed by the actual workshop, then debriefing or presentation of outputs for sharing and critiquing purposes. The interactive touch screen television was used during the presentation of mini-lessons as the basis of workshop and also during presentation of students' outputs for sharing and critiquing purposes. The written outputs of students in the form of a research proposal were evaluated using a validated rubric. The results of the study showed significant improvement in the writing skills of students from both groups. The findings implied the effectiveness of workshop assisted by interactive touch screen television in enhancing students' skills in crafting a research proposal. Therefore, innovative ways of teaching significantly produce a meaningful learning.

1 INTRODUCTION

As time passed by, methods of teaching and even instructional materials kept changing. Despite the fact that there is no such thing as the best method or instructional material, teachers have become resourceful, creative, and innovative in their way of teaching. One of the modern methods of instruction is a workshop. A workshop in its pedagogical context is a type of educational program commonly designed for a group of people, in which the content is practical, and specific to the needs, interests and affinities of the group, which empowers teamwork and mutual support among participants [1]. In workshops, there are series of interactive activities perform by the participants as a form of training which differs in content and length.

Workshop as a teaching method is recognized around the globe because of its capability to make the teaching-learning process active, creative, and socially interactive. For instance, a study on Readers ' Writers' Workshop (RWW) in the secondary English classroom, and its findings showed that RWW is an effective tool for engaging students and assisting them in developing positive attitudes toward reading practice [2]. Meanwhile, another study explored the points of view of teachers handling mathematics who applied workshop method in classroom settings. The results showed that participants appreciated the math workshop as an effective instructional method to enhance teaching and learning in mathematics [3]. However, some teachers implementing workshop method experienced discomfort and worries since workshop approach involves a deep understanding of personal, curricular, instructional and epistemological foundations [4]. Thus, it encouraged school leaders to consider the teachers' need of time and space to take risks and reflect on their responsibilities.

On the other hand, technology has turned out to be an essential part of our usual life [5]; hence, many countries consider technology as one of the keystones of educational reform as to integration in teaching because of its capability to make teaching-learning

process easy, active, creative, innovative and interactive. For instance, a study on the role of technology-based instructional design and its effect on the instructors' professional advancement in English as a foreign language and proved effective [6]. At the same time, the effectiveness of interactive educational software in developing instructional design skills among teachers at Al Baha University was demonstrated [7]. Modern technology is integrated in teaching on a huge scale to aid learning across different disciplines [8]. Based on the above-mentioned facts, it clearly manifests that technology plays a great role in today's educational system.

In the Philippines, educators and scholars also emphasize educational reform [9]. As times change, educational policy also changes, which implies a great effect on the teaching and learning methods. Indeed, it is a major challenge for teachers to become resourceful and innovative in teaching and designing instructional materials. At the same time, it has been stressed that today's world is a territory of continuous changes, which pushes teachers to undergo intensive training on modern teaching methods [10]. At the tertiary level, the Commission on Higher Education (CHED) focuses on Outcomes-Based Education (OBE). According to Liwanag (2023) [11], the teaching method in OBE is learner-centered, which aims to assess the outcomes of students' learning. It is based on the constructivist view of John Piaget, which focuses on students, not teachers. Indeed, implementing the workshop method in teaching college students, assisted by technology like interactive television, is learner-centered.

In the university where the researcher is teaching, innovation is also given attention by administrators and teachers. However, some innovations in teaching are limited. For instance, the College of Teacher Education Research Office has organized a yearly workshop for third-year students enrolled in the Research Subject. However, only the group leaders in every section are invited to join because of a budget scarcity. This could not address the concerns of the whole class in a research subject. Many students experience difficulty in writing academic papers because of lack of skills in writing and critical thinking [12]. At the same time, the inputs of the teachers are the only basis in crafting a research paper. So, they emphasized that employing effective teaching strategies will result to a meaningful learning. Moreover, it was found out that language proficiency and writing skill are some of the main factors that affect students' ability in writing a research paper [13]. They recommended that teachers should employ practical teaching approaches and techniques which encourage students to appreciate research. Also, it was recommended by Auddya (2023) [14] that teachers are encouraged to have enough knowledge in doing and teaching research. Hence, the researcher was motivated to use workshop as a teaching method in writing a research proposal. This initiative would prepare the students for the real world of thesis writing during their third year level.

In 2024, the school administration provided ten units of interactive touch screen televisions in the College of Teacher Education where the researcher is employed as a college teacher. This is new in the college since the usual audio-visual aid in the classrooms is smart televisions. It was emphasized that using technology and software is important in research to achieve authentic and effective results [15]. Fortunately, the researcher was assigned to classrooms with interactive touch screen televisions, which paved the way for her to use such modern technology during workshops in the classroom. It was found out that workshops deliver a platform that assist researchers to identify and explore essential issues in a certain realm by giving ways for comprehending multifaceted work and knowledge processes that are reinforced by technology [16].

Some studies have already been conducted that focused on workshops, such as effectiveness of a workshop in teaching accounting subject [2], and the evaluation and effectiveness of a teacher training workshop to improve teaching competencies and outcomes [17] - [23]. There is still a gap since no studies have been conducted that employed workshop as a teaching method to provide 'hands-on' experiences to college students in crafting a research proposal. On the other hand, studies about integrating technology in the educational field are already conducted [6], [24], [25], focusing on the integration of technology in teaching and learning English as a foreign language and proving effective. Additionally, the use of smartphones with free mobile software applications for tertiary education and manifested positive effect [26]. Specifically, few recent studies on the instructional use of media platform like televisions were conducted and revealed positive impact [27] - [30]. There are no conducted studies assisted by technology like interactive touch screen television in presenting mini-lessons and outputs in workshops for crafting a research proposal.

The above-mentioned gaps and issues are the reasons which motivated the researcher to conduct this study to test the effectiveness of workshop in the classroom as a teaching method, aided by the interactive touch screen television as an audio-visual

material. Statistical treatments such as arithmetic mean, standard deviation, mean gain difference and t-test of independent samples were utilized to analyze the data objectively.

2 OBJECTIVES

Generally, this study was conducted to test the impact of the workshop with interactive touch screen television on the tertiary students' skill in writing a research proposal.

Specifically, it sought to answer the following questions:

1) What is the level of skills of students in writing a research proposal from experimental A and experimental B based on the result of:
   - pre-writing,
   - post writing
2) Is there a significant difference in students' level of skill in writing a research proposal before and after the intervention?
3) Is there a significant difference in the mean gain score of students based on the result of pre-writing and post-writing?

3 METHODOLOGY

This study employed a quantitative method, particularly a quasi-experimental design. The researcher utilized the respondents' research proposal outputs during pre-writing and post-writing activities for experimental A and B in a time-series approach. This is to test the effect of the workshop method with interactive touch screen television on tertiary students' level of skills in writing a research proposal. The interactive touch screen television was used to assist the researcher in presenting the mini-lessons as basis of the workshop. The workshop was based on model [31], which includes the presentation of mini-lessons, followed by the worktime or actual workshop, then debriefing for sharing and critiquing purposes.

The respondents of this study were first year college students from the College of Teacher Education, Sultan Kudarat State University – ACCESS Campus, ECJ Montilla, Tacurong City enrolled in Purposive Communication subject, in which writing an academic paper like research proposal was a part of the final term period. This requirement prepared the students to write a thesis during their third-year level. The respondents were 25 pairs from the Bachelor of Secondary Education major in Filipino and 27 pairs from the Bachelor of Secondary Education major in English, who were chosen through purposive sampling. The pairing was done to exercise collaborative effort and learning. This is supported by findings [32] that formative peer feedback has a positive impact in the quality of the academic paper.

The instrument used in evaluating students' outputs in the form of a research proposal was an adopted rubric from the university utilized by the College of Teacher Education in evaluating research proposals. The rubric was slightly modified by the researcher to meet the specific objectives of the study, which was then validated by three professors holding doctoral degrees. Then, Confirmatory Factor Analysis (CFA) was done to statistically test if the observed data from the rubric used fit a pre-specified theoretical model of what the rubric is intended to measure. Five professors with doctoral degrees evaluated the students' outputs using the rubric from experimental A and B in the form of a research proposal.

To assess the average of the scores of the pre-writing and post-writing test, mean and standard deviation was used. To calculate the mean, the observed values were added and divided by the number of respondents. This process is conveniently expressed by the symbol:

The standard deviation was calculated after

$$\bar{x} = \frac{(\Sigma x)}{n}$$

finding the mean of the set of data. Next, the mean was subtracted from each data point to find the deviations. Then, each deviation was squared, and summed up these squared values and then divided the sum by the number of data points minus one to find the variance. Finally, the square root of the variance was taken to get the standard deviation.

$$SD = \sqrt{\frac{\Sigma(x-\bar{x})^2}{n-1}}$$

To find out the difference between the skills of students of both pre-writing and post writing, mean gain scores were utilized. It was done simply by subtracting the mean of the pre –writing from the mean of the post- writing.

Paired-Sample t-test was also used to match the pairs of data, such as the pre-writing and post-writing scores for the same group of participants. It determines if the mean scores changed significantly after the treatment.

To calculate the paired t-test, the difference (d) for each paired observation was computed first, then

followed by finding the mean and standard deviation (sd) of these differences. The t-statistics was then calculated as $t = (\bar{x}d - \mu d) / (sd / \sqrt{n})$, where n is the number of pairs.

This study emphasized ethical considerations by warranting students' permission to become respondents. The researcher ensured that students' outputs were treated with confidentiality. The researcher properly recognized the citations and references used.

4 RESULTS AND DISCUSSION

Table 1 shows the results of pre-writing and post writing activities. In the pre-writing activity, the E\experimental A obtained a mean of 2.11 (SD=.12) with a description of "disagree" based on the evaluation and an interpretation of "unsatisfactory' while experimental B obtained a mean of 2.61 (SD=.89) with a description of "slightly agree" and an interpretation of "satisfactory". The data implies that the writing skill of students from experimental A is low while experimental B slightly knows how to craft a research proposal before the intervention. Many students find it difficult to write an academic paper because of lack of skills in writing and critical thinking [12]. At the same time, the inputs of the teachers in class are the only basis in crafting a research paper. So, they emphasized that applying an effective teaching strategy would result to meaningful learning.

In the post-writing activity, the students from experimental A has a mean of 4.54 (SD=.02) with a description of "strongly agree" from the evaluators with an interpretation of "very satisfactory" while experimental B obtained a mean of 4.52 (SD=.03) with a description of "strongly agree", with an interpretation of "Very Satisfactory". The data reveals that employing workshop in the classroom assisted by interactive touch screen television was effective to enhance students' skill in crafting a research proposal. The findings are similar to a study [2] where Readers' Writers' Workshop was found out as an effective tool for engaging students and assisting them in developing positive attitudes toward reading. In terms of technology, study on the instructional use of interactive television conducted in a special education course had revealed a positive impact [26]. Indeed, workshops aided by the interactive touch screen television gained a fruitful learning.

Table 2 reveals that there is a significant difference between the level of skill in writing a research proposal of students from experimental A before and after the intervention since the t-computed value (3.46) is higher than the T-tabulated (.019) at .05 level of significance. It indicates that the workshop method assisted by interactive touch screen television improved the skills of students in writing a research proposal. This finding is reinforced by a study [3] which showed that participants appreciated the math workshop as an effective instructional method to acquire a meaningful teaching-learning in mathematics. Although the study focused on enhancing mathematics skill and not on the writing skill in crafting a research proposal but workshop was employed and proved effective. As to technology-based teaching-learning, it was recommended [30] based on the study results that the utilization of television shall be a recognized innovation and shall be encouraged to maximize its use for learning activities in the academe.

Table 1: Results of writing skill of students in crafting a research proposal from Experimental A (BSED-Filipino) and Experimental B (BSED-English) during pre-writing and post-writing.

Test	Group	N	Mean	SD	Description	Interpretation
Pre-writing	A	25	2.11	.12	Disagree	Unsatisfactory
	B	27	2.61	.89	Slightly Agree	Satisfactory
Post-writing	A	25	4.54	.02	Strongly Agree	Very Satisfactory
	B	27	4.52	.03	Strongly Agree	Very Satisfactory

Table 2: Results of T-test in the level of skill of students from experimental a in writing a research proposal before and after the intervention.

Intervention	N	Mean	SD	T-computed	T-tabular	Interpretation
Before	25	2.11	.12	3.46	.019	Significant
After	25	4.54	.02			
@=.05 level of significance						

Table 3: Results of T-test in the level of skill of students from experimental b in writing a research proposal before and after the intervention.

Intervention	N	Mean	SD	T-computed	T-tabular	Interpretation
Before	27	2.61	.89	3.68	.021	Significant
After	27	4.52	.03			
@=.05 level of significance						

Table 4: Results of T-test in the mean gain score of students based on the result of pre-writing and post-writing.

Variable	N	Mean Gain	SD	T-computed	T-tabular	Interpretation
Experimental Group A	25	2.43	.32	3.23	.03	Significant
Experimental Group B	27	1.91	.52			
@=.05 level of significance						

Table 3 manifests that there is a significant difference between the level of skill in writing a research proposal of students from experimental B before and after the intervention since the T-computed value (3.68) is higher than the T-tabulated (.021). The data reveals that the workshop as teaching intervention, aided by the interactive touch screen television, was effective in enhancing the students' skill in crafting a research proposal. In a study, it was found out that workshops were effective in teaching accounting [33]. Another study focused on the use of smartphones with free mobile software applications for tertiary education and manifested a positive effect [26]. In addition, it was emphasized that media platforms like television, radio, and internet have extended the accessibility of instruction beyond the borders of traditional classrooms [27]. Indeed, media has transformed teaching-learning from passive to active engagement. Thus, it personalizes learning, tailors content and addresses individual needs and interests.

Table 4 shows a significant difference between the mean gain score of students from experimental A and B based on the result of pre-writing and post-writing since the t-computed value (3.23) is higher than the t-tabulated (.03). It reveals the clear manifestation of the effectiveness of workshops in the classroom assisted by the use of interactive touch screen television as an innovative teaching method and instructional material for writing a research proposal. This is supported by a study [6] on the role of technology-based instructional design and its effect on teachers' professional advancement in English as a foreign language and proved effective. Another study found that workshops provide a platform that assist researchers to identify and explore essential factors in a given domain by providing ways for understanding multifaceted work and knowledge processes that are reinforced by technology [16].

5 CONCLUSIONS

Modern teaching methods such as workshops provide hands-on activities for students that result in meaningful learning, as revealed by the findings obtained through statistical tools such as the arithmetic mean, standard deviation, mean gain difference, and the t-test of independent samples. Moreover, the use of technology, particularly interactive touch screen television during workshops, has demonstrated great potential in enhancing students' learning outcomes in crafting a research proposal because of its ability to make the teaching-learning process easier, more active, and more interactive.

In general, conducting classroom workshops supported by interactive touch screen television provides accessible, socially interactive, and practical learning experiences for students, which promotes the core principles of outcomes-based education.

6 RECOMMENDATIONS

Based on the findings of the study, teachers are encouraged to continue exploring practical and innovative approaches in teaching research in order to sustain and further improve meaningful teaching-learning experiences. Integrating modern technologies such as interactive touch screen television during workshops may help facilitate more engaging and effective instruction.

However, certain limitations should be considered, including the availability of technological resources and the level of teachers' skills in conducting workshops and utilizing modern technologies. Therefore, educational institutions should also support teachers by providing adequate training and access to necessary technological tools.

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SECTION 3

DATA ANALYSIS AND PROCESSING

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Emotions and Textual Feature Analysis for Motion Picture Association of America (MPAA) Rating Classification

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Keywords: Machine Learning, MPAA Rating, Movie Scripts, LightGBM, Multi-Class Classification, TF-IDF.

Abstract: Movies represent one of the most important media that combine narrative components with visual and auditory elements to entertain or inspire viewers. The Motion Picture Association of America (MPAA) is a prominent rating system that plays a great role for audience to select an appropriate film. This rating system is important because it helps parents filter the content to protect their children from unsuitable movies. It also assists audiences in their own choice. Traditionally, MPAA ratings are assigned by reviewers manually and this, in turn, leads to inconsistency, subjectivity, and time-consuming. This research introduces an automated method for predicting MPAA rating by using the scripts feature with the emotion feature that aiming to enhance classification accuracy and provide a more reliable assessment of age appropriateness. Scripts are preprocessed and converted into term frequency-invert document frequency (TF-IDF) vectors to capture significant linguistic patterns. Moreover, emotional features are extracted from movie scripts using transformer-based models due to their contextual understanding capabilities. These features are integrated to form a multi-class output. In this study, the LightGBM algorithm is applied as a gradient boosting technique. Experimental findings indicate that combining emotion features alongside textual representations enhances prediction accuracy in comparison to the use of scripts alone. The model achieves 84.2% and 84.6 for the weighted F1-score and the accuracy metric, respectively. This supports the effectiveness of the proposed model in predicting MPAA ratings from both movie scripts and emotional features.

1 INTRODUCTION

Movies are important means of cultural expression and artistic in people's life. They are not just a means of entertainment, but movies also a tool for social and intellectual influence. Film classification is an essential step in regulating the film industry and ensuring it reaches the appropriate audience. This enables viewers to choose films that suit their interests and preferences. It also contributes to directing audiences to age-appropriate content through age rating. Thus, movie classification is an effective way to protect children and sensitive groups from inappropriate content. In addition, it facilitates production and distribution companies to market films more accurately. This can also enhance the viewing experience by setting audience expectations before watching a film. Creators can rely on movie classification as it directs them towards a specific genre that reflects their artistic vision [1].

The age appropriateness of films has been recommended by censorship bodies through rating certificates. There are two main organizations specialized in performing this task. The former is the Motion Picture Association of America (MPAA) in the United States of America, whereas the latter is the British Board of Film Classification (BBFC) in the United Kingdom [2]. These two organizations build their ratings based on films' content. MPAA ratings have a wide practical value where parents can depend on them as a guideline to determine which movies are appropriate for children. Media service providers such as Amazon and Netflix may use these ratings to enable age-appropriateness filters. This mainly relies on movie scripts as a means to determine their content [3].

The MPAA uses five film ratings to guide audiences. The first one relates to the General type (G) that is suitable to all ages with no offensive content, nudity, or significant violence. The second one is Parental Guidance (PG) that may contain

unsuitable material for children with moderate violence and brief nudity. Parents Strongly Cautioned (PG-13) is the third type which includes warns content that may be inappropriate for viewer under-13 years with occasional use of substances, strong language, and minimal sexual content. Fourthly, Restricted (R) requires parent accompaniment for under-17 year due to adult content, including strong language, violence, sexuality, or substance use. Finally, No One Under 17 (NC-17) prohibits anyone under 17 from viewing due to explicit sexual scenes, extensive harsh language, or excessive violence, though it is not classified as obscene or pornographic [4].

A wide range of data sources can be utilized for the automatic classification of movies into age appropriateness rating. One of the important data sources available about movies is movie scripts, which contain only conversations between characters, which is considered the foundation of filmmaking. Movie scripts instruct how a scene should be filmed in addition to telling the audience what is happening. It is a screenplay-formatted document that authors, directors, and actors can use to help them prepare for their parts [5].

Traditionally, MPAA ratings are assigned manually by human reviewers. This approach is often considered time-consuming, subjective, and inconsistent. It may also affect the rating decision due to personal bias or differing interpretations of content. Consequently, there is a growing need for an automated and reliable method to predict MPAA ratings objectively. Developing such a system can enhance consistency, reduce human effort, and support filmmakers, distributors, and audiences in understanding content suitability more efficiently.

The present study addresses this problem by automatically predicting MPAA ratings for movies based on their textual content. The task is formulated as a multi-class classification problem. The input parameters include both textual features and other features that are extracted via the Transformer model. The classification process is based on the LightGBM algorithm, which predicts the most appropriate MPAA class for each movie. To evaluate the model performance, the accuracy and weighted F1-score are used as main criteria for assessment.

The key aims of this research are twofold. First, it develops an automatic method to predict MPAA movie ratings using textual script data with emotions that are extracted from the entire script. The distilled version of RoBERTa (DistilRoBERTa) [6]as a Transformer model is employed for feature extraction. The extracted features are combined with Term Frequency–Inverse Document Frequency (TF-IDF) features and they are fed into the LightGBM[7] model for multi-class prediction purposes. Second, the research addresses the limitations of the sequence length constraints existing in Transformer architectures. To achieve such aims, it seeks to answer the following research questions:

1) How can emotion features extracted from a Transformer-based model improve the performance of MPAA rating prediction in comparison to traditional text-based representations alone?
2) Which method can effectively handle the input sequence length limitation of Transformer models when processing long movie scripts for emotion feature extraction?
3) To what extent the combination of different features can contribute to achieving higher accuracy and interpretability in automated MPAA rating prediction?

Based on such aims and research questions, this research achieves the following contributions:

1) Proposing an automatic model for predicting MPAA rating based on fusion term weighting features with emotion features extracted from a Transformer-based model.
2) Presenting a method for handling the length size limitation of the input sequence processing that exists in the Transformer model during the emotion feature selection process.
3) Achieving a new performance benchmark for this task with 84.2% for the weighted F1-score and accuracy was 84.6%.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature and related work. Section 3 presents the dataset and methods used. Section 4 reports the proposed model phases. Section 5 presents and analyzes the experimental results. Finally, Section 6 provides conclusions and outlines potential future research directions.

2 LITERATURE REVIEW

This study attempts to address the gap related to extracting emotion features by employing a Transformer-based model that is capable of capturing contextual and fine-grained affective cues within movie scripts. Unlike lexicon-based methods such as the Name Entity Recognition (NRC) emotion lexicon [1][8], which assigns static emotion

values to individual words without considering their contextual meaning, the proposed approach utilizes the DistilRoBERTa-base model ("j hartmann/emotion-english-distilroberta-base"). It was trained on the GoEmotions dataset. This model enables the extraction of context-dependent emotional representations that better reflect the underlying sentiment and intensity of movie narratives. This study also introduces a method to overcome the input length limitation in Transformer-based emotion extraction by segmenting and aggregating emotional representations across script chunks.

The movie scripts are typically long and complex narratives, often exceeding the maximum input length (512 tokens) that Transformer-based models can process. This constraint causes loss of contextual and emotional information, leading to incomplete emotion representation. This method can preserve emotional continuity and ensures that long movie scripts are fully analyzed, capturing both local and global emotional contexts. By integrating these emotion features with statistical linguistic representations derived from TF-IDF, the proposed framework improves the accuracy and reliability of automated MPAA rating prediction.

Many studies were accomplished on age rating classification. These studies varied in using either traditional machine learning techniques or artificial neural network models. It was found that this literature utilized a single data type such as text data, images, or based on multiple form to achieve better accuracy results.

To our knowledge, the first published research about predicting MPAA rating was accomplished by Shafaei et al. [8]. The research works on predicting the suitability of movies for children and young adults based on movie scripts, relying on the MPAA rating system as a benchmark. A deep learning model was proposed by using a Recurrent Neural Network (RNN) with an attention layer. This incorporates movie genres and emotions in conversations to predict the five MPAA ratings. The experiment shows that the model achieves a weighted F1-score of 78% which outperforms traditional machine learning methods by 6%. The study highlighted that bad word lists alone are insufficient for MPAA rating prediction. Therefore, including multiple factors such as violence, language, and thematic material can enhance the prediction. The model performance was improved when genre and emotion vectors were included.

Another research introduced in [1] presents a task of predicting the MPAA rating of movies using their scripts to assess age suitability for children and young adults. The Long Short-Term Memory (LSTM) model was leveraged here with the attention mechanism and it incorporated both emotion and genre vectors for predicting MPAA ratings. The pre-trained Global Vectors for Word Representation (Glove) was used as a word embedding method which can preserve the semantic information. Based on model performance, the weighted F1-score was 81.6% which outperforms traditional machine learning methods by 7%.

In [9] a multi-modal method was proposed based on deep learning methods to automate the age-suitability rating of movie trailers. A new dataset, the Multi-modal Movie Trailer (MM-Trailer) that contains 1,443 trailers and their corresponding age-suitability ratings. The research combines audio, video, and text modalities to improve prediction accuracy, demonstrating that multi-modal approaches outperform single models. A specialized neural network architectures were assigned for each modality. RNNs were for text and audio, and CNN-LSTM were for video. The results indicated that the Gated Multi-modal Unit (GMU) fusion method yields the highest performance, significantly improving upon the best single modality model. Based on the experimental results of the GMU fusion variant, it achieved a weighted F1 score of 86.06% that outperforms other fusion methods and single modality models. It should be noted that the output result in this study is a binary classification, where the film is classified as suitable for all audiences or restricted and specific to a specific audience.

Another research study [3] introduced a multimodal approach for predicting the film age appropriateness with MPAA and BBFC. It combined textual and visual features. The subtitles and synopses were used in textual data, while the movie poster was used as the visual data. Several deep learning and machine learning models were utilized for textual and visual data.

ResNet, Inception and NASNet were used for visual feature extraction, while the TF-IDF method was used for textual feature selection. The study demonstrated that textual features provide a strong predictor of MPAA ratings, while images provide complementary information. The experimental result shows that combining both modalities leads to a higher accuracy than using either alone, which highlights the value of multimodal fusion in movie rating research. The best accuracy result was accomplished using xgboost model with only three

class output (PG, PG-13, R), with 81.1% for MPAA and 66.8% for BBFC.

The research study introduced in [4] proposed using bidirectional LSTM models that were integrated with an attention mechanism to introduce MPAA multi-class movie rating prediction. The study was based on 12000 textual script data and presents four models to evaluate the best one using different feature extractors as Bidirectional Encoder Representations from Transformers (BERT) and A Robustly Optimized BERT Pretraining Approach (RoBERTa). According to the research results, the bad word frequency model achieves the best output with an accuracy metric of 56% classification of movie ratings.

3 MATERIALS AND METHODS

3.1 Movie Dataset

The dataset contains a movie corpus with a collection of 5.562 movie script files, and movie poster files. Furthermore, there is a metadata file contains information about movies, such as IMDB_ID, Title, Genre, MPAA_rating, Actors, Poster source, Director, and year [1]. The movie scripts file contains the whole conversations among characters which was saved in a separated file. There are five MPAA rating types in this dataset that are G, PG, PG-13, NC-17 and R. Figure 1 shows the distribution of these ratings.

3.2 The Emotional Extraction Model

The DistilRoBERTa-base model is a faster and smaller version of the RoBERTa [10] transformer model that is designed to retain most capabilities of the RoBERTa model, while reducing computational complexity and inference time. The distillation technique consists of training a smaller model to replicate the functioning of a larger model, allowing for effective deployment in resource-constrained settings. The DistilRoBERTa-base emotion model is fine-tuned on annotated emotion recognition datasets such as GoEmotions [11]. It contains 27 emotion categories, or six emotion types plus a neutral class. The fine-tuning enables the model to categorize input text into specific emotions by leveraging the contextual embeddings generated by the DistilRoBERTa architecture. This model balances between performance and efficiency that make it suitable for large-scale emotion detection or real-time tasks in applications, such as movie script analysis. Combining emotion features with other data into multimodal frameworks enhances the understanding of narrative tone in the used data to improve the performance in tasks such as MPAA rating prediction.

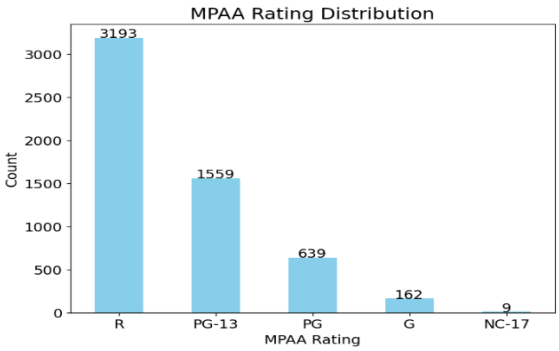


Figure 1: MPAA_rating distribution over movies.

3.3 Textual Feature Extraction

This research uses simple method to select script features by using TF-IDF technique.TF-IDF is the most known feature extraction technique that converts text data, such as summaries or scripts, into numerical vectors suitable for machine learning models. TF-IDF highlights terms that are most informative [12] for distinguishing between movie rating. For instance, words such as "kill" or "blood" may indicate a strong signal for R rating of films. Other words such as "school" or "friendship" are more indicative of G or PG rating. The general terms such as movie or story are assigned less weight because they provide little information regarding age suitability.

The ability of capturing specific vocabulary related to various rating types makes TF-IDF an effective representation for machine learning classifiers such as SVM, Random Forest, and ensemble models, thereby improving predictive accuracy in multi-label movie genre classification tasks. To compute TF-IDF as Equation (3), two variables should be calculated: TF based on (1) and IDF from (2) as in [13].

$$TF_{t,d} = \frac{f_{t,d}}{\sum_{t \in d} f_{t,d}}, \quad (1)$$

where, $f_{t,d}$ is the number of present of term t in document d, $\sum_{t \in d} f_{t,d}$ indicates the overall count of terms t within document d

$$IDF_{(t,D)} = log\ \frac{N}{|\{d \in D : t \in d\}|}, \quad (2)$$

where N = total number of documents d in corpus D and $|\{d \in D : t \in d\}|$ denotes the count of documents that include the term t.

$$\text{TF-IDF} = \text{TF} * \text{IDF}. \quad (3)$$

3.4 LightGBM Model

LightGBM [7] stands for Light Gradient Boosting Machine, which is a type of gradient boosting framework developed by Microsoft. LightGBM has two significant techniques that make it outperforms the traditional XGBoost model in the memory consumption and processing speed. The first technique is Gradient-based One-Side Sampling (GOSS) that emphasizes selecting samples using their gradients, giving priority to those with greater gradients during training. Exclusive Feature Bundling (EFB) is the second one that enhances memory utilization by grouping unique features, enabling more effective processing and quicker training, while maintaining performance levels substantially. It effectively handles a substantial number of data instances and a large variety of features. Therefore, these two features make the LightGBM model much quicker and more scalable than traditional GBM.

4 THE PROPOSED MODEL

This study presents a multi-class classification model for predicting four types of MPAA rating categories. This is based on fusion extracted emotional and script features using a powerful machine learning model. Before that, the data must pass through a preprocessing stage to introduce clear data for use in the suggested model.

4.1 The Preprocessing Stage

Preprocessing is a crucial step in any Natural Language Processing (NLP) tasks that affect a model's performance [14]. To use the movie script for subsequent analysis, text normalization and cleaning procedures are needed. Many cleaning procedures were utilized in this research, such as is lowercasing, stopwords removal and alphabetic filtering. The lowercasing process converts the entire input script into lowercase alphabetical to ensure consistency in letter casing, thereby minimizing sparsity in the token space. Another preprocessing procedure is the elimination of stopwords, which discards common English stopwords such as “and”, “is”, and “the”. This method was implemented using the NLTK library. Lastly, an alphabetic filtering process was applied to keep only tokens made up of purely alphabetic characters. This helps remove numbers, punctuation, and other non-letter symbols that usually do not add meaningful semantic value.
There is another preprocessing step related to the imbalance state of the class label. This involves identifying and removing the rare labels. This can potentially improve the performance of the learning model by reducing noise and preventing overfitting on the underrepresented class. Based on Figure 1, which illustrates the distribution of five MPAA rating labels, the NC-17 rating class was removed since it had low occurrence frequency over other rating.

4.2 The Classification Stage

The proposed model is illustrated in Figure 2. It is based on three stage to achieve the goal of predicting MPAA rating. The first one is related to feature extraction from TF-IDF after cleaning the textual script during the preprocessing stage. The spaCy English language library, which is considered a natural language processing was used in the text cleaning procedure to standardize the movie script before the feature extraction stage. The cleaning process converts all script texts into lowercase, removes unnecessary symbols, and tokenizes the content into linguistically meaningful units. The tokens are then rejoined to form coherent sentences, while correcting spacing around punctuation marks to preserve natural text structure. This procedure ensures that the scripts are linguistically consistent, noise-free, and properly formatted for TF-IDF and emotion feature extraction.

In this study, the number of TF-IDF features was set to 12,000, aiming to capture as many as possible representative and informative terms from the movie scripts. This dimensionality was chosen to balance between computational efficiency and feature richness, ensuring that both common and distinctive

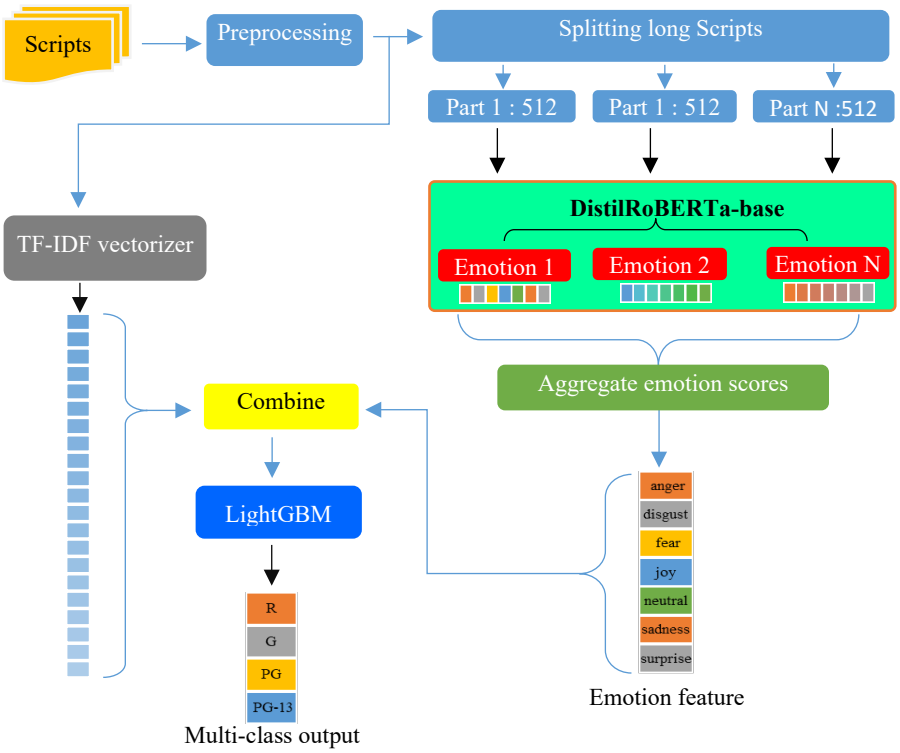


Figure 2: The proposed MPAA rating classification model.

linguistic patterns contribute to MPAA rating prediction. The second one is associated with the emotional feature extraction, that was accomplished using a trained DistilRoBERTa-base model. It was published on the Hugging Face website under the "j-hartmann/emotion-english-distilroberta-base" title. The model was trained over the GoEmotions dataset to predict six emotions namely, "anger", "disgust", "fear", "joy", "sadness" and "surprise", and "neutral" type.

The Transformer-based emotion recognition is designed to capture contextual emotional nuances in text by leveraging deep semantic representations rather than relying on keyword-based emotion lexicons. The maximum input sequence that the DistilRoBERTa model can process is 512 tokens, where the medium token length in the used script exceeds 2000 tokens based on the calculation sequence size.

In this state, this model was unable to extract the emotion features from the entire script. Therefore, we proposed a method to address this limitation by using the chunking method. It splits the long-cleaned script into small chunks with 512 tokens, where every chunk is passed to the emotional model to extract the emotion vector for that chunk. This process is repeated to complete the remaining chunks. The individual emotion features per chunk are aggregation together to produce the final vector that represents the emotion tone in the script.

This emotion feature vector was combined with the TF-IDF vector to form the final feature vector that is fed into the LightGBM classifier. The data was split into 80% for training and 20% for testing to ensure that the model was trained on the majority of the samples, while preserving a separate portion for unbiased evaluation. Since the dataset had an imbalanced class distribution, as shown in Figure 1, creating the necessity to address this issue, which can be model-based or data-based. This study utilizes a class weights strategy, which is a type of model-based approach to tackling class imbalance. Typically, models tend to be biased towards the majority classes since the loss function influences heavily by the frequent labels. When employing the class weights technique, the loss for minority classes increases and this, in turn, leading the model to focusing more on rare categories during the training stage. This modification enhances the capability of the model to classify rare labels accurately and results in more balanced performance across all classes, especially in application such as MPAA rating

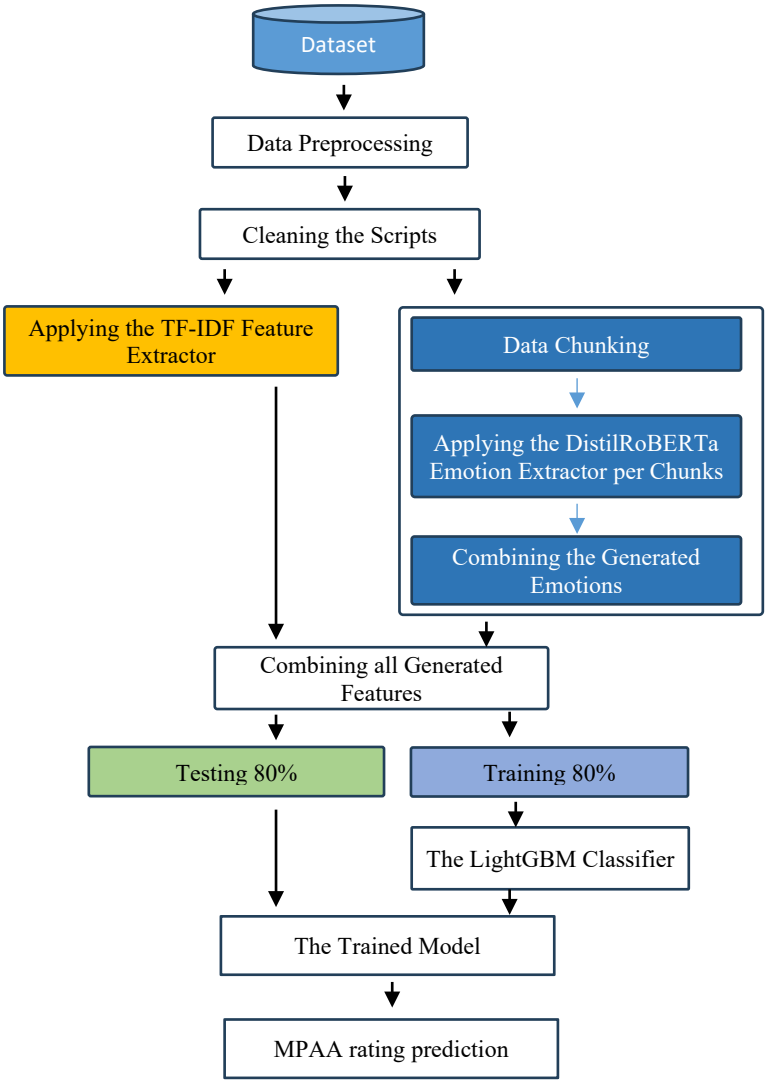


Figure 3: The entire model flowchart.

prediction. In this system, some categories may be significantly less common than others. After completing the training process with four multi-class labels, the LightGBM model can predict the MPAA rating of a given script by applying the SoftMax activation function on the output probabilities. The class with the highest probability is selected as the final predicted rating. This can be either G, PG, PG-13, or R. The overall workflow of the proposed MPAA rating prediction model is illustrated in Figure 3. It presents the main processing stages that begin from data preprocessing and chunking, until TF-IDF feature extraction and emotion representation using the DistilRoBERTa model. The extracted features are then fused and passed to the LightGBM classifier to predict the final MPAA categories.

5 RESULTS

The proposed model was tested with four machine learning models namely, Support Vector Machine (SVM), Naive Bayes (NB), Random Forest (RF) and XGBoost. Moreover, the findings of other studies were compared with the proposed model to demonstrate its efficiency. Both evaluation metrics, Accuracy and the Weighted F1-Score [15], were used to comprehensively evaluate the model's performance in the multi-class

classification task. Accuracy measures the overall proportion of correctly classified samples, while the Weighted F1-Score accounts for class imbalance by averaging the F1-scores of each class according to their support. Achieving high accuracy and a strong weighted F1-Score indicates reliable predictions across all classes. This demonstrates that the model not only performs well overall but also maintains balanced performance for both the majority and minority classes.

Some studies relied on the weighted F1–Score metric [16] This is based on the normal F1 – Score. This metric is presented in (4). It can provide more weight to classes that have more samples.

$$F1_{\,weighted} = \sum_{i=1}^{k} \frac{n_i}{N} . F1_i \,, \qquad (4)$$

n_i = number of true samples in class i , $F1_i$ = F1-score for class i , N = total number of samples.

Table 1 shows the model performance using various numbers of selected TF-IDF features. This is starting from 10000, 12000, and 15000 vector features. The model was evaluated using 5000 features, but it achieved a lower result than 10000 features. The LightGBM model outperformed other models. The weighted F1-Score, and accuracy were 84.2, 84.6, respectively.

Table 1: Evaluation of TF-IDF feature variants.

Method	10000 TF-IDF		12000 TF-IDF		15000 TF-IDF	
	weighted F1–Score	Accuracy	weighted F1–Score	Accuracy	weighted F1–Score	Accuracy
SVM	68.1	66.5	68.3	66.6	68.5	66.9
Naive Bayes	42.2	57.7	42.2	57.7	42.2	57.7
Random Forest	70	72.7	69.8	73.1	66.3	70.2
XGBoost	82.2	82.2	83.8	83.3	83.4	83.5
LightGBM	83.1	83.3	**84.2**	**84.6**	83.9	83.9

Table 2 illustrates the model performance in comparison with previous studies. The best result was achieved by the suggested model, except for the findings presented in [9]. However, it should be clear that the output of [9] is binary classification only. The accuracy value was 84.6 after integrating emotional features, while the weighted F1-Score metric was 84.2. The model was tested without using the emotional feature to identify the contribution of utilizing the emotion features. Its overall results were 83.7 and 83.8 for both weighted F1-Score and accuracy metric, respectively. This result was obtained when using the top 12000 features during the calculation TF-IDF feature, where it represents the best value that was selected based on experimental results.

Table 2: Performance comparison with literature.

Study	Method	weighted F1–Score	Accuracy
[8]	RNN	78	-
[1]	LSTM + Glove	81.6	-
[9]	CNN-LSTM + GMU	86.06	-
[3]	TF-IDF + ResNet, Inception	-	81.1
[4]	bidirectional LSTM	-	56
Our model	TF-IDF , LightGBM	**83.7**	**83.8**
Our model	TF-IDF + emotion , LightGBM	**84.2**	**84.6**

6 CONCLUSIONS

Movie ratings prediction plays a crucial role to ensure appropriate content for audience. It provides guidance for parents and audience by categorizing films according to their thematic content, language, and level of violence. This makes the importance of creating a model to classify movie ratings automatically.

This research presented a multi-class classification model for predicting four MPAA ratings based on a fusion approach. It integrated the script features extracted from TF-IDF and emotion features obtained from the DistilRoBERT model. This study demonstrated that Transformer-based emotion features enhance MPAA rating prediction beyond traditional method such as NER. Due to the limitation of sequence length processing, this present study introduced a new method based on a chunking method to address this constraint. It enabled the model to acquire the emotion tone from the entire script length. TF-IDF vectors, along with the emotion vector, were combined and passed into the LightGBM classifier to predict the height of movie ratings. Based on the results, the combination approach showed an enhancement in the prediction of MPAA ratings by achieving high accuracy and weighted F1-score.

The class weight technique was utilized to handle the imbalance state of labels, where some classes had far fewer samples than others. The presented results showed that integrating the

emotional features enhanced the performance of the LightGBM model. Furthermore, the suggested model result was compared with earlier literature based on the evaluation metric. This research findings outperformed previous studies with 84.2 and 84.6 for weighted F1–score and Accuracy, respectively.

Regardless of the research findings, some limitations should be addressed to open the door for future research. First, a multimodal approach can be applied to multiple data types. This may help generalize the proposed model. Moreover, applying more methods to address the class imbalance may enhance the model's performance. Finally, the proposed model should be applied on another rating way to improve its efficiency and applicability.

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A Big Data Framework for Automated Environmental Risk Stratification Using a Composite Hazard Index and Unsupervised Clustering

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Keywords: Big Data, Environmental Risk Assessment, Composite Hazard Index, Unsupervised Clustering, Decision Support System.

Abstract: The proliferation of IoT-based environmental monitoring networks has led to an exponential increase in air quality data, creating a significant challenge for effective and timely risk assessment. Traditional analysis methods often struggle to convert this vast volume of raw data into actionable insights for decision-makers. This paper introduces a novel big data framework designed to automate the process of environmental risk assessment through a two-stage analytical approach. First, we propose a Composite Hazard Index (CHI), a quantitative metric that normalizes and aggregates data from disparate pollutants into a single, interpretable risk score for each monitoring location, incorporating expert-defined weights to reflect the relative toxicity of different substances. Second, this index, along with normalized pollutant profiles, is used as input for an unsupervised clustering algorithm (K-Means) to automatically stratify locations into distinct risk tiers (e.g., Low, Medium, High). A key novelty of our approach is a descriptive analysis method that identifies the primary pollutants, or "key risk drivers," responsible for the elevated hazard levels in high-risk clusters. The framework was validated using a real-world dataset from a public air quality monitoring network. The results demonstrate the system's ability to successfully identify high-risk "hotspots," quantify their danger level, and pinpoint the specific pollutants contributing to the threat, thereby providing a powerful, data-driven tool for proactive environmental management.

1 INTRODUCTION

The global challenge of air pollution, with its well-documented adverse effects on public health and ecosystems, has entered a new era defined by data abundance [1]. The widespread deployment of low-cost Internet of Things (IoT) sensors and citizen science initiatives has generated unprecedented volumes of high-frequency environmental data [2]. This "data deluge" presents a dual opportunity and challenge. On one hand, it offers the potential for granular, real-time analysis of environmental dynamics. On the other, the sheer volume, velocity, and heterogeneity of this data overwhelm traditional analytical approaches, creating a critical gap between data availability and the ability to derive actionable intelligence for environmental governance [3].

1.1 Related Work

A review of current scientific literature reveals several distinct but often fragmented approaches to this problem. A significant body of research focuses on predictive modeling, employing machine learning techniques like Long Short-Term Memory (LSTM) networks to forecast pollutant concentrations [1, 2]. While valuable for short-term warnings, these models often operate on raw concentration values and do not inherently provide an integrated assessment of the overall environmental risk, which is often a product of multiple interacting pollutants. Furthermore, their accuracy is fundamentally dependent on the quality of input data, a major issue given the known reliability concerns of low-cost sensors [3].

Another prominent research direction involves the use of exploratory data analysis, particularly unsupervised clustering algorithms, to identify spatial patterns and pollution "hotspots" [4, 5]. For instance, Hu et al. (2022) applied clustering and spatial statistics to classify urban pollution levels, successfully identifying distinct geographical patterns [5]. More advanced techniques like co-clustering have been used to simultaneously group spatial and temporal objects, revealing complex interactions [6]. However, a common limitation of these methods is their descriptive nature. They effectively answer the question "Where are the problem areas?" but often fall short of quantifying the severity of the risk or identifying its primary drivers, leaving interpretation to human experts.

To bridge this gap, hybrid methodologies have emerged, combining clustering with physical-chemical receptor models like Positive Matrix Factorization (PMF) to link clusters with specific emission sources (e.g., traffic, industry) [7, 8]. This approach provides a powerful diagnostic tool, offering insights into the "Why?" behind pollution patterns. Nevertheless, it typically requires detailed and costly chemical speciation data, which is not available from standard monitoring stations that measure bulk pollutants like PM2.5 or CO.

1.2 Problem Formulation

Based on the identified gaps in the existing literature, this research addresses the challenge of transforming high-volume, multi-pollutant monitoring data into a prioritized and interpretable risk assessment. The problem can be formally stated as follows:

GIVEN:

1) A raw dataset of time-series air quality measurements from a set of m monitoring locations, where each record contains a location identifier, timestamp, pollutant type, and concentration value.
2) A set of regulatory standards (e.g., Maximum Allowable Concentrations) for each of the n monitored pollutants.
3) A set of expert-defined raw weights representing the relative health impact or importance of each pollutant.

FIND:

1) A single, quantitative Composite Hazard Index (CHI) for each of the m locations that represents the integrated environmental risk.
2) An automated stratification of the m locations into a predefined number of K discrete risk tiers (e.g., "Low," "Medium," "High") based on their pollutant profiles and overall CHI.
3) For the highest risk tier, an identification of the key pollutants (risk drivers) that are the primary contributors to the elevated risk level, quantified by a comparative metric.

2 MAIN PART

2.1 Research Methodology

2.1.1 Data Pre-Processing and Profile Generation

The initial stage transforms raw, heterogeneous time-series data into a structured, analysis-ready format. This is a prerequisite for any meaningful analysis of environmental indicators [9]. The process involves several steps:

1) Data from disparate sources and timeframes are consolidated into a unified structure, with each record containing a location identifier, timestamp, pollutant type, and concentration value.
2) Absolute concentration values are converted into a dimensionless, universally comparable metric of risk. This is achieved by dividing each measurement by its corresponding regulatory standard, such as the Maximum Allowable Concentration (MAC). A value of 2.5 after this step is unequivocally interpreted as "the concentration is 2.5 times the established safe limit," regardless of the pollutant.

3) To handle missing data and irregular measurement intervals, time-series for each unique "location-pollutant" pair are resampled onto a regular time grid (e.g., daily). Gaps are filled using linear interpolation, a reasonable assumption for environmental processes over short intervals.
4) The processed time-series data is aggregated over a defined analytical period (e.g., one year) to create a static "environmental profile" for each monitoring location. This profile is represented as a feature vector where each element is the mean MAC-normalized value for a specific pollutant. This results in a feature matrix X of size $m \times n$, where m is the number of locations and n is the number of pollutants.

2.1.2 Composite Hazard Index Calculation

To move from a multi-pollutant profile to a single, rankable measure of overall danger, we introduce the CHI. The calculation is a three-step process:

1) The feature matrix X (containing mean MAC-normalized values) is further normalized to a scale of $[0,1]$ to ensure all risk factors contribute equally to the index calculation, regardless of their original range. For each pollutant j, the normalized value for location i is calculated as:

$$x_{norm,ij} = \frac{x_{ij} - \min(X_j)}{\max(X_j) - \min(X_j)}, \quad (1)$$

where $\min(X_j)$ and $\max(X_j)$ are the minimum and maximum mean values for pollutant j across all locations.

2) The framework allows for the incorporation of expert knowledge by assigning weights to each pollutant based on its perceived toxicity or local importance. A user-defined vector of raw weights $W_{\text{raw}} = [w_{\text{raw},1}, \ldots, w_{\text{raw},n}]$ is normalized to sum to 1:

$$W_{norm,j} = \frac{w_{raw,j}}{\sum_{k=1}^{n} w_{raw,k}}. \quad (2)$$

The use of expert-defined weights, rather than a machine learning approach, is a deliberate decision that prioritizes interpretability, control, and practicality.

Experts assign these transparent weights based on established public health knowledge, pollutant toxicity, and regulatory standards, such as reference concentrations (RfCs). This ensures the resulting risk score is scientifically justified and aligned with health priorities, for example, by giving a higher weight to PM2.5 due to its significant cardiorespiratory effects. This method also allows authorities to adjust weights based on local concerns or new toxicological findings.

From a practical standpoint, a machine learning model would require a large, labeled dataset linking pollution mixes to verified health outcomes, which is exceptionally rare. Therefore, the expert-driven system provides a more robust and operationally feasible solution for decision support, while still allowing for future refinement through machine learning as suitable data becomes available.

3) The CHI for each location i is computed as the weighted sum (scalar product) of its normalized pollutant vector and the normalized weight vector:

$$CHI_i = \sum_{j=1}^{n} x_{norm,ij} \cdot w_{norm,j}. \quad (3)$$

The result is a vector $R = [\text{CHI}_1, \ldots, \text{CHI}_m]$, where each CHI_i is a value in $[0,1]$ representing the integrated environmental hazard at that location.

2.1.3 Unsupervised Risk Stratification (Auto-Clustering)

This stage uses the generated profiles and indices to automatically group locations into meaningful risk tiers. We employ the K-Means clustering algorithm, but with a novel feature engineering approach to guide the process.

1) Instead of clustering on the pollutant profiles alone, we create an augmented feature vector Z_i^* for each location i. This vector concatenates the normalized pollutant profile with its calculated CHI:

$$Z_i^* = \left[x_{norm,j1}, x_{norm,j2}, \cdots, x_{norm,jn}, CHI_i \right]. \quad (4)$$

This augmentation forces the clustering algorithm to consider not only the similarity in the mix of pollutants but also the overall level of hazard as captured by the CHI.

2) The K-Means algorithm is applied to the set of augmented feature vectors {Z1*, … Zm*}. For

risk stratification, the number of clusters K is fixed (typically K =3) to represent “Low Risk,” “Medium Risk,” and “High Risk” tiers. The algorithm partitions the locations into K clusters C={C1, …Ck} by minimizing the within-cluster sum of squares (inertia):

$$\arg\min_{C} \sum_{k=1}^{K} \sum_{Z_i^* \in C_K} \left\| Z_i^* - \mu_k^* \right\|^2, \qquad (5)$$

where μ_k^* is the centroid of cluster C_k.

3) After partitioning, the clusters are ordered based on the average CHI of their constituent locations, ensuring that Cluster 0 corresponds to the lowest risk and Cluster K–1 to the highest.

2.1.4 Key Risk Driver Analysis

The final stage provides an interpretable explanation for why a cluster is classified as high-risk. Instead of relying on complex statistical tests that may be unreliable with small sample sizes, we use a straightforward descriptive metric.

For each pollutant j, we calculate its mean value (from the original, un-normalized feature matrix X) within the “High Risk” cluster (C_{High}) and the “Low Risk” cluster (C_{Low}). The Risk Multiplier (M_j) is then calculated as the ratio of these means:

$$M_j = \frac{mean(X_j \ in \ C_{High})}{mean(X_j \ in \ C_{Low})}. \qquad (6)$$

Such a mathematical model is easily integrated and can be implemented both in public monitoring information systems [10] and used for municipal monitoring.

2.2 Results and Discussion

The proposed framework was validated using the "Air Quality Monitoring from EcoCity" dataset [11], a comprehensive, real-world collection of public monitoring data from the city of Vinnytsia, Ukraine. For this validation, higher expert weights were assigned to particulate matter (PM2.5), reflecting its significant impact on respiratory health, as detailed in the "Risk Factor Importance" charts within the generated reports. The analysis was conducted for two periods: a historical review from January 1, 2021, to September 9, 2023, and a forecasted period from September 9, 2023, to October 9, 2023, to assess both retrospective patterns and future trends.

2.2.1 Risk Index Calculation and Stratification

After pre-processing the historical data, the framework calculated a CHI for each monitoring station. The results, visualized in the "Comprehensive Risk Index" chart (Fig. 1), revealed a stark distribution of risk, with CHI scores ranging from approximately 0.1 to a severe outlier of 0.786 [12].

The subsequent risk stratification, using K-Means with K=3, produced a clear and actionable grouping of the stations into three distinct risk tiers. The results for the historical period are summarized in Table 1.

The clustering process unequivocally isolated a single station, s-1612, as the sole member of the "High Risk" cluster. This result immediately focuses analytical and regulatory attention on a specific geographical point of major concern. The quantitative nature of the CHI provides critical context for this classification; its index of 0.786 is nearly double the index of the "Medium Risk" station and four times higher than the "Low Risk" average [13].

This is further confirmed by the spatial distribution map (Fig. 1), where s-1612 is represented by a significantly larger circle, visually identifying it as a risk "hotspot".

2.2.2 Identification of Key Risk Drivers

To understand the underlying cause of this anomaly, the Key Risk Driver Analysis was performed. This analysis compares the average, real-world pollutant concentrations (in mg/m³) between the "High Risk" cluster (containing only s-1612) and the "Low Risk" cluster. The results for the historical period, detailed in the "In-Depth Analytical Report" (Fig. 2), were striking, as shown in Table 2.

The analysis provides an unambiguous conclusion: the extreme risk associated with station s-1612 is overwhelmingly driven by particulate matter. The average concentrations of PM10 and PM2.5 at this location are over 400-500 times higher than in the safest zones. In contrast, the levels of gaseous pollutants like CO and NO_2 are nearly identical across all clusters [14]. This finding effectively rules out generalized urban pollution (e.g., from traffic) as the primary cause and strongly suggests the presence of a powerful, localized source of particulate emissions in the immediate vicinity of station s-1612. The "Anatomy of Risk" chart (Fig. 2) visually corroborates this, showing that the risk index for s-1612 is almost entirely composed of the contribution from PM2.5.

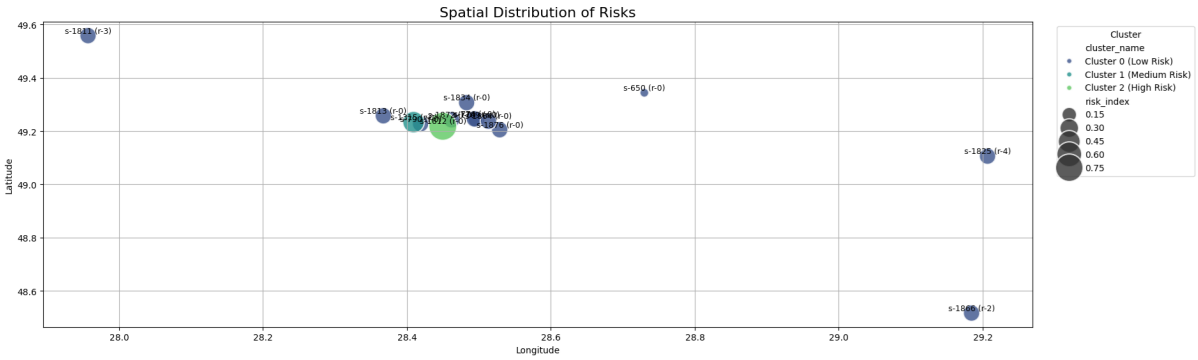


Figure 1: Spatial distribution of the CHI across monitoring stations for the historical period (2021-01-01 to 2023-09-09).

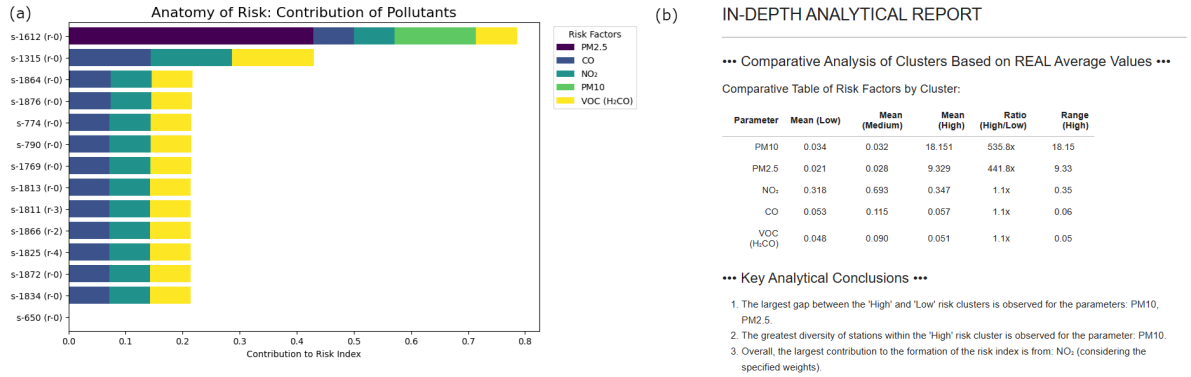


Figure 2: Analytical dashboard for the historical period (2021-01-01 to 2023-09-09): a) pollutant contribution to the CHI for each station and b) summary of the Key Risk Driver Analysis.

Table 1: Results of Risk Stratification on Historical Data (2021-01-01 to 2023-09-09).

Risk Tier	Low Risk	Medium Risk	High Risk
Cluster ID	0	1	2
Number of Stations	12	1	1
Average CHI	0.197	0.430	0.786
Key Stations Identified	s-650, s-1834, s-774, etc.	s-1315	s-1612

Table 2: Key Risk Driver Analysis for Historical Data.

Pollutant	Mean (Low Risk Cluster)	Mean (High Risk Cluster)	Risk Multiplier
PM10	0.034	18.151	535.8x
PM2.5	0.021	9.329	441.8x
NO_2	0.318	0.347	1.1x
CO	0.053	0.057	1.1x

2.2.3 Spatio-Temporal Dynamics and Regional Impact

The framework's ability to analyze forecasted data provides crucial insights into the stability of these risk patterns. The analysis of the forecasted period shows that the risk structure at the station level remains remarkably stable. Station s-1612 persists as the single occupant of the "High Risk" cluster, and while the forecasted absolute concentrations are lower, the risk multipliers for PM10 (30.6x) and PM2.5 (24.5x) remain an order of magnitude higher than for any other pollutant. This indicates that the identified pollution source is likely constant and its impact will persist, making it a priority for long-term strategic intervention.

Aggregating the results to a regional level further clarifies the impact of this local hotspot. The regional analyses for both the historical (Fig. 4) and forecasted (Fig. 3) periods consistently identify region r-0 – the region to which station s-1612 belongs – as the area with the highest environmental risk. The "Structure of Risk" charts for both periods demonstrate that the elevated risk in region r-0 is driven by a disproportionately high contribution from particulate matter, a direct consequence of the anomaly at s-1612. This highlights the system's ability to trace the impact of a micro-level issue on macro-level regional assessments.

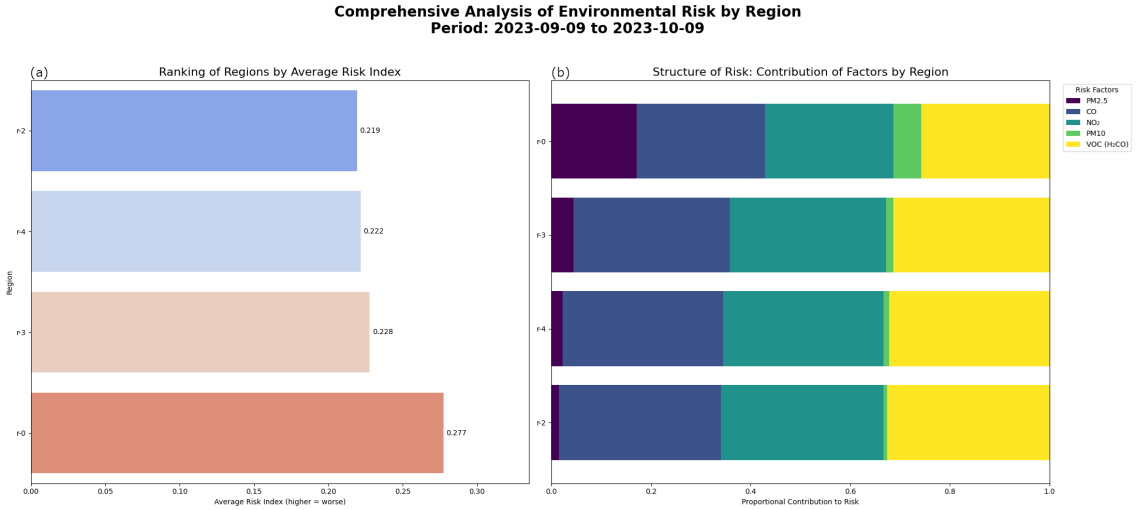


Figure 3: Regional environmental risk analysis for the forecasted period (2023-09-09 to 2023-10-09): a) Ranking of regions by average CHI and b) proportional contribution of each pollutant to regional risk.

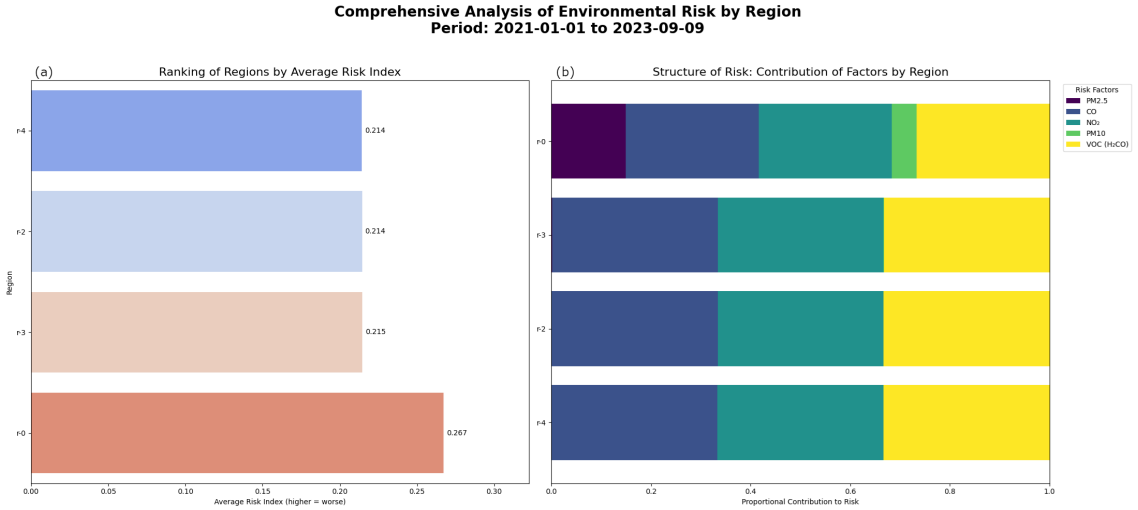


Figure 4: Regional environmental risk analysis for the historical period (2021-01-01 to 2023-09-09): a) ranking of regions by average CHI and b) proportional contribution of each pollutant to regional risk.

3 CONCLUSIONS

This paper presented a novel big data framework for the automated analysis and stratification of environmental risk. In response to the challenge of processing vast and heterogeneous data from modern monitoring networks, our methodology provides a structured, multi-stage pipeline that transforms raw measurements into actionable intelligence.

The core contributions of this work are twofold. First, the development of a CHI offers a method to synthesize complex, multi-pollutant data into a single, quantitative, and rankable score of environmental danger. Second, we demonstrated a guided clustering approach that uses these comprehensive risk profiles to automatically stratify monitoring locations into clear risk tiers, effectively identifying "hotspots." The framework's ability to then pinpoint the key risk drivers for these high-risk zones provides a crucial diagnostic capability.

The scientific novelty of this work is multi-faceted and lies not only in the individual components but, crucially, in their synergistic integration into a single analytical pipeline that bridges the gap from raw data to decision support. Specifically, this novelty is defined by:

1) A methodological shift in data pre-processing, which moves beyond standard cleaning to include a risk-based normalization step. By converting absolute concentrations into a dimensionless metric of multiplicity relative to MAC, the framework transforms the data into an inherently risk-aware format before any analysis is performed.
2) An improved approach to exploratory analysis, where the Composite Hazard Index is not merely an output but a critical input for the clustering algorithm. This "guided clustering" technique forces the stratification to be based not just on the similarity of pollution profiles, but on the overall level of danger, thereby moving beyond descriptive grouping to perform prescriptive risk stratification.

Validation on a real-world dataset confirmed the framework's effectiveness. It successfully isolated a single location of extreme risk, quantified its hazard level relative to other areas, and unambiguously identified particulate matter (PM10 and PM2.5) as the primary cause. This result exemplifies the system's potential to provide clear, evidence-based, and targeted insights for environmental agencies, enabling a shift from reactive responses to proactive, data-driven management. While acknowledging limitations such as the reliance on expert weights, the proposed framework represents a significant step towards building more intelligent, interpretable, and effective decision support systems for environmental security.

ACKNOWLEDGMENTS

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Predicting Trial-to-Paid User Conversion in Video Streaming Platforms Using Session-Based Behavioral Data

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Keywords: Trial-to-Paid Conversion, Video Streaming Analytics, Marketing Optimization, Machine Learning.

Abstract: Predicting user conversion from free trial to paid subscription is an important task for video streaming platforms. It helps to improve marketing efforts and reduce unnecessary costs. Traditional marketing methods, such as sending many emails, often give low results and can cause users to lose interest. This study is based on behavioral data from 60,000 trial users of a video streaming platform, of whom about 10% converted to paid subscriptions. The dataset includes user metadata, session activity, and conversion outcomes, providing rich signals of viewing behavior. In this paper, we present a machine learning approach to predict the chance of conversion by analyzing user behavior during the trial period. We test both single-model and ensemble-model classifiers, using features based on session activity, device usage, and content variety. Since only 10% of users convert, we tested different sampling strategies, including SMOTE, undersampling on 10,000 samples, and a combined SMOTE + undersampling approach. The results show that ensemble methods, especially Random Forest, perform better than simpler models in terms of F1-score and recall for the minority class. Furthermore, the feature importance analysis shows that session duration, number of used devices, and diversity of content are strong indicators of conversion. These findings show that machine learning can support more effective and targeted marketing, with less unwanted communication.

1 INTRODUCTION

Online video content has become a regular part of people's lives and plays an important role in different industries. The growth of social networks and various streaming platforms has strongly supported this trend. As the video streaming environment continues to change, it is influenced by user behavior, market developments, strong competition, and cultural factors [1]. From user perceptions and platform adoption to multicultural engagement, live sports, gaming, and the rise of ad-supported models, a range of powerful forces are redefining the future of streaming.

Video streaming platforms frequently offer trial periods to attract new users, hoping a portion will convert into paying subscribers. However, in most cases, only a small number of users decide to pay. Prior work has shown that trial design and user behavior during trials strongly affect conversion outcomes [2]. Despite this, marketing strategies often rely on mass email campaigns, which not only have low effectiveness but can also reduce user interest and trust.

This paper explores a data-driven alternative by analyzing behavioral session data to predict which users are likely to convert to paid subscriptions. By examining patterns such as session duration, device usage, and viewing diversity, we aim to identify behavioral signals that distinguish potential subscribers from non-converting users.

From a scientific perspective, this study contributes in several ways. First, it formalizes the trial-to-paid conversion problem as a supervised classification task based on session-level behavioral dynamics- an area that remains underexplored in existing literature. Second, it provides an empirical comparison of multiple imbalance-handling strategies (SMOTE, undersampling, and hybrid methods) and quantifies their effects on model generalization and minority-class recall, both of which are critical for reliable prediction in imbalanced business datasets. Third, by combining interpretable models with feature importance analysis, the study identifies measurable behavioral indicators of subscription intent, bridging machine learning methods with actionable marketing insight.

2 RELATED WORK

User conversion prediction is a well-studied problem in domains such as e-commerce, mobile applications, and online media services. In the context of video streaming, predicting trial-to-paid conversion is particularly relevant due to the high customer acquisition costs and the competitive nature of the subscription-based content industry.

Many studies have focused on using user behavior to understand engagement and to predict whether a user will stay or leave. For example, Wang et al. [3] studied how users browse in e-commerce websites to predict whether a session will lead to a purchase, while recent work on mobile platforms has focused on churn and subscription renewal prediction using behavioral features [4]. These works show the importance of user interaction data, including frequency, recency, and type of usage, as predictors of intent.

In the streaming field, platforms like Netflix and Hulu have used methods like collaborative filtering and sequence modeling to recommend content and guess future user actions. However, these systems mainly focus on what content to recommend, not on predicting who will pay for a subscription. Gupta et al. [5] showed the value of session-level metrics, including session frequency and time spent on content, in understanding user satisfaction and predicting retention.

Different machine learning models have been used in conversion prediction, such as logistic regression, decision trees, and ensemble models like random forest and gradient boosting. Some newer methods include deep learning and models like LSTM that can work with time-based data. However, in business, simpler models are often preferred, because they are easier to understand and give clear results that can be used in planning.

Class imbalance is a common issue in conversion prediction because the number of users who convert is often much smaller than the number who do not. To address this problem, several studies have proposed resampling methods. Recent surveys [6] confirm that resampling remains an effective approach, while Wongvorachan and Bollen [7] showed that hybrid strategies combining SMOTE with undersampling often achieve better recall and F1-score for the minority class. Recent theoretical work has also analyzed the properties of SMOTE, providing insight into why it improves minority-class prediction [13].

In practical marketing situations, where it is important to identify as many potential converters as possible, SMOTE is usually preferred. It helps balance the dataset by generating synthetic samples of the minority class without losing any information from the majority group.

Our approach aligns with this stream of research by focusing on interpretability and business impact. We use real session data from a video streaming service to build classification models that can predict conversion. Compared to other studies, we give more attention to extracting practical conversion insights, such as typical time to conversion and device-based engagement, which can directly guide marketing strategy. Unlike prior studies that primarily focused on churn prediction or content recommendation, our work directly targets the trial-to-paid conversion stage in video streaming, which is a critical but less explored business challenge. The novelty of this paper lies in combining behavioral session features with imbalance-aware modeling to produce interpretable insights that can directly guide marketing strategies.

3 DATASET AND PREPROCESSING

This study uses behavioral data collected from a video streaming platform that offers free trial periods to new users. The dataset includes information from 60,000 trial users, and around 10% of them (5,500 users) converted to paid subscriptions. The data is grouped into three main sources: user metadata, session activity, and conversion records.

User information included identifiers, subscription outcomes, and the timing of conversions, along with additional attributes such as email-related metadata. Session-level behavior was captured from detailed activity logs, covering aspects such as session duration (start and end times), device characteristics (operating system, device type, application version, and user agent), and content engagement through channel identifiers. A clear conversion marker was added to distinguish users who subscribed.

Before analysis, sensitive or irrelevant attributes - such as regional information, technical edge data, and unique identifiers - were removed. Sessions with incomplete device information were also excluded to ensure data consistency and completeness.

To ensure the dataset only contained meaningful behavioral signals, all users (both converted and non-converted) who did not generate any session activity were excluded. Since these users provide no interaction data, they bring no value for the algorithms, and the absence of sessions makes it impossible to learn any useful patterns about their behavior. This filtering step reduced noise in the

dataset and improved the quality of subsequent analyses.

3.1 Feature Construction

To prepare the data for machine learning, we aggregated the session-level records into user-level features representing engagement, device usage, browsing diversity, and temporal activity. These behavioral variables capture different aspects of how users interact with the platform during the trial period and serve as predictors of conversion. A detailed description of all constructed features and their assessment criteria is provided in Table 1.

3.2 Data Preparation

Categorical fields representing primary device operating system and device type were encoded into numerical categories using LabelEncoder to facilitate model training. Users without recorded sessions were retained in the dataset, with all behavioral fields initialized to zero, preserving the original trial population distribution.

The resulting dataset consists of one row per user, with aggregated behavior features and a binary label showing if the user converted. This structured data serves as input for the next predictive modeling phase.

4 METHODS AND CLASS IMBALANCE

4.1 Model Selection and Training Setup

The proposed framework for predicting trial-to-paid user conversion is summarized in Figure 1, which outlines the complete data flow, from data preprocessing and feature construction to resampling, model training, and evaluation. Each user is represented by a feature vector containing aggregated behavioral metrics (e.g. unique_channels, total_duration_min, unique_user_agents), paired with a binary label indicating conversion (1 = paid, 0 = not paid).

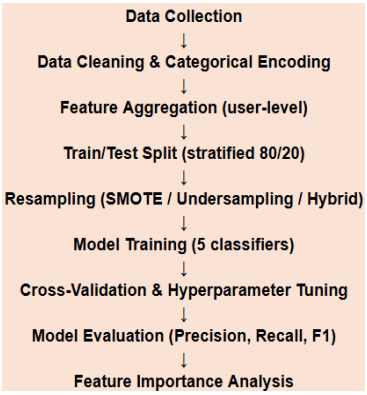


Figure 1: Training and evaluation pipeline for trial-to-paid user conversion prediction.

The task is formulated as a supervised classification problem, where each user is denoted as a feature vector x_i and a corresponding label $y_i \epsilon \{0,1\}$, where $y_i = 1$ represents a converting user. The goal is to learn a classification function $f(x_i)$ that estimates the probability of conversion $P(y_i = 1 \mid x_i)$, where probabilistic estimates are obtained directly or through calibrated model outputs, depending on the algorithm.

Since our main aim is to find users with high potential to convert during the trial period, we selected machine learning models that are both well-known and easy to interpret.

We employed five classification algorithms: Logistic Regression, Support Vector Machine (SVM) with both linear and RBF kernels, Random Forest, k-Nearest Neighbors (kNN), and Extreme Gradient Boosting (XGBoost). Logistic Regression serves as a strong baseline, providing interpretable feature weights and allowing easy understanding of each predictor's contribution to the model [8].

Table 1: Variables used for behavioral assessment.

Variable	Description	Assessment Criterion
total_session_count	Total number of sessions during	Indicate frequent platform usage
total_duration_min	Total minutes watched during	Indicates stronger engagement
avg_duration_min	Average session duration	Measures consistency
max_duration_min	Longest single session	Captures peak engagement
unique_device_type_count	Number of device types used	Indicates cross-device behavior
unique_os_count	Number of OS used	Indicates cross-device behavior
unique_channels	Unique content channels watched	Reflects content exploration
unique_user_agents	Distinct user agents per user	Indicates multi -environment use
active_days	Days between first and last session	Measures sustained activity

SVM is effective for high-dimensional problems, and its RBF kernel captures non-linear relationships between features [9]. Random Forest, an ensemble of decision trees, performs robustly even when features are noisy or correlated [10]. kNN is a simple yet effective algorithm that classifies users based on their similarity to others [11]. XGBoost is a powerful gradient boosting algorithm designed for structured data, offering regularization and efficient handling of missing values, which often improves predictive performance [12].

Hyperparameter optimization was performed for the Random Forest and Gradient Boosting models using grid search combined with 3-fold cross-validation.

4.2 Handling Class Imbalance

One of the main challenges in our modeling task is the imbalance between the two classes. Only about 10% of users convert to paid subscriptions, while 90% do not. This large imbalance can cause classification models to focus too much on predicting the majority class, which reduces their ability to detect converting users, the group that is most important for the business.

To address this issue, we used three different resampling strategies aimed at improving model sensitivity to the minority class: SMOTE (Synthetic Minority Over-sampling Technique) [13], random undersampling [14], and a combined approach involving both methods [15].

SMOTE is a popular oversampling technique that creates synthetic samples of the minority class by interpolating between existing examples. This helps to balance the dataset without removing any data from the majority class and improves the model's ability to learn from minority patterns.

In contrast, random undersampling reduces the number of samples in the majority class to match the size of the minority class. While this method may result in the loss of potentially useful information, it reduces model bias toward the dominant class and often speeds up training.

The undersampling size of 10,000 samples was chosen after preliminary experiments that balanced computational efficiency and class representation. This number ensured that all 5,500 positive (converted) users were retained while reducing the majority class to a comparable scale, thus maintaining a 1:1.8 ratio that improved model recall without excessive information loss.

To further balance the trade-off between sample diversity and information preservation, we also applied a hybrid method that combines SMOTE and random undersampling. This approach enhances minority class representation while retaining a meaningful portion of majority class examples.

By applying and comparing these resampling strategies and focusing on imbalance-aware evaluation, we aimed to improve the model's ability to detect converting users while preserving stable overall performance.

5 EXPERIMENTAL SETUP

In order to evaluate the predictive performance of various classification algorithms for trial-to-paid user conversion, we adopted a holdout validation approach, splitting the dataset into 80% training and 20% testing using stratified sampling to preserve the ratio of converted and non-converted users in both subsets. This way, the evaluation simulates real-world conditions, with the same class imbalance that exists in production.

Each machine learning model was trained on the same training data and tested on the same test set to ensure fair comparison.

To optimize performance, we conducted hyperparameter tuning using 3-fold cross-validation on the training data. For Random Forest, we varied the number of trees (n_estimators), tree depth (max_depth), and minimum samples required to split a node (min_samples_split). For Gradient Boosting, we tuned the number of estimators, maximum depth, and learning rate. The tuning was guided by the F1-score, which is more appropriate for imbalanced data because it balances precision and recall for the minority class (converted users). After tuning, we selected the best settings for each model and evaluated their performance on the test set.

The evaluation metrics - precision, recall, F1-score, and accuracy - follow the standard definitions provided by Powers (2011) [16].

In this study, these metrics were used to assess both overall model correctness and the ability to identify likely paying users (the minority class). Because the dataset is highly imbalanced, recall and F1-score were given higher priority than accuracy. Recall indicates how many actual converters were correctly identified, while precision reflects the reliability of these predictions. The F1-score, as the harmonic mean of precision and recall, provided a single measure balancing both aspects. Accuracy was used only as a general indicator of stability across models.

6 EXPERIMENTAL RESULTS

The experimental results for the baseline classification models are summarized in Tables 2-4. All models were trained using three sampling strategies to address class imbalance: SMOTE, undersampling on 10,000 samples, and a combined SMOTE + undersampling approach, and were evaluated on the original test set. This decision avoids data leakage and gives a more realistic view of how the models would perform on new, unseen users in real deployment scenarios.

Focusing first on the undersampling approach, Table 2 presents the baseline performance of all five models. Among the simpler models, Logistic Regression achieved an accuracy of 0.9596 but showed moderate F1-score (0.78) and recall (0.77) for the minority class, highlighting its limitations in capturing complex, non-linear user behavior. k-Nearest Neighbors provided slightly better recall for the minority class (0.81) but lower precision (0.76), reflecting a trade-off between detecting positive converters and avoiding false positives.

Table 2: Baseline model performance with undersampling.

Model	Accuracy	Precision	Recall	F1-score
Logistic Regression	0.9596	0.78	0.77	0.78
Decision Tree	0.9699	0.83	0.84	0.84
k-Nearest Neighbors	0.9592	0.76	0.81	0.78
Random Forest	0.9775	0.90	0.85	0.87
Gradient Boosting	0.9795	0.92	0.85	0.88

Tree-based models performed better than simpler approaches. The Decision Tree classifier reached an F1-score of 0.84 for the positive class, showing balanced precision and recall. Random Forest and Gradient Boosting achieved the best results, with Gradient Boosting reaching the highest accuracy (0.9795) and F1-score (0.88), while Random Forest delivered a strong F1-score (0.87) and high precision (0.90), highlighting its ability to identify likely converters while limiting false positives.

Building on these results, we further analyzed Random Forest and Gradient Boosting. Random Forest consistently delivered the strongest overall performance, as shown in Table 3. Among the sampling strategies, undersampling provided the highest F1-score for the minority class (0.87), while recall was slightly higher for the combined SMOTE + undersampling approach (0.86). SMOTE alone achieved slightly lower performance across all metrics.

Table 3: Random Forest performance across sampling methods.

Sampling Method	Accuracy	Precision	Recall	F1-score
SMOTE + Undersampling	0.9747	0.86	0.86	0.86
Undersampling	0.9775	0.90	0.85	0.87
SMOTE	0.9759	0.89	0.84	0.86

Gradient Boosting achieved the highest F1-score for class 1 with undersampling (0.88), though recall was slightly lower (0.85) than with SMOTE or the combined method (0.86) (Table 4). This clearly shows that undersampling provides the best overall balance between precision and F1-score for accurately identifying likely paying converters.

Table 4: Gradient Boosting performance across sampling methods.

Sampling Method	F1-score	Recall
SMOTE + Undersampling	0.87	0.86
Undersampling	0.88	0.85
SMOTE	0.87	0.86

The confusion matrices for Random Forest and Gradient Boosting provide further insight into performance with the undersampling approach. Random Forest correctly classified 939 of 1,108 positive cases, with 169 misclassified as negative and 104 negatives as positive (Figure 2). Gradient Boosting correctly identified 943 positives, misclassifying 165 as negative and 83 as positive (Figure 3). These results show that both ensemble methods achieve high accuracy for the minority class while keeping false positives low, confirming their suitability for conversion prediction.

Overall, these results demonstrate that ensemble methods, particularly Random Forest and Gradient Boosting, are the most effective models for trial-to-paid conversion prediction, and that undersampling on 10,000 samples consistently provides slightly better performance than SMOTE or the combined approach, making it the preferred strategy for this task.

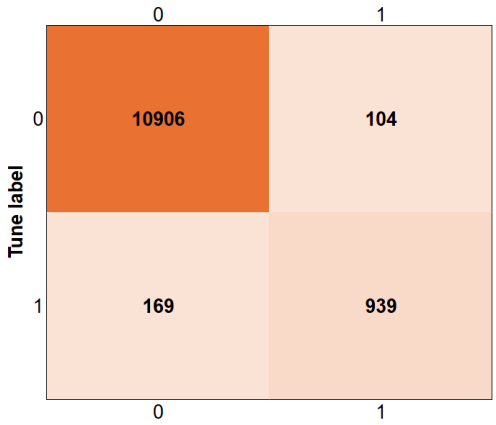


Figure 2: Confusion matrix for Random Forest using undersampling.

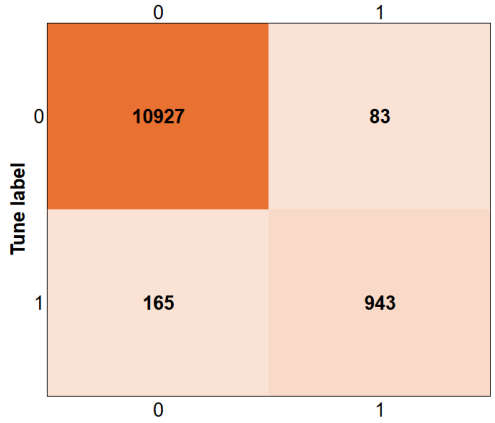


Figure 3: Confusion matrix for Gradient Boosting using undersampling.

7 FEATURE IMPORTANCE ANALYSIS

Understanding which user behaviors influence trial-to-paid conversion is critical for improving prediction and guiding marketing strategies. To investigate this, we analyzed feature importance using the Random Forest classifier on the undersampled dataset. The results are shown in Figure 4, which presents the relative importance of the top features.

The Random Forest model distributed importance across multiple features, with max_duration_min (0.204) and unique_user_agents (0.192) emerging as the strongest predictors of conversion. These features capture both the intensity and diversity of user engagement: users who spend longer maximum time on content and access the service from multiple user agents are more likely to convert. Total_duration_min (0.169) and unique_device_type_count (0.103) also contributed significantly, emphasizing that both overall engagement and device diversity play an important role. Features such as avg_duration_min (0.095) and unique_channels (0.088) had lower, yet meaningful contributions, suggesting that while average session duration and content variety matter, they are secondary to maximum engagement and user agent diversity.

Figure 4 clearly shows that engagement intensity and device diversity are the most influential factors in predicting trial-to-paid conversion, which aligns with expectations: users who interact more deeply and flexibly with the platform during the trial period are more likely to convert. This insight can help inform targeted marketing efforts, such as recommending content to highly engaged users or providing incentives for multi-device usage.

8 CONCLUSIONS

This study explored the prediction of trial-to-paid user conversion in video streaming platforms using behavioral session data and machine learning. Five classification models were evaluated - Logistic Regression, Decision Tree, k-Nearest Neighbors, Random Forest, and Gradient Boosting - under three imbalance-handling strategies: SMOTE, random undersampling, and a hybrid combination of both.

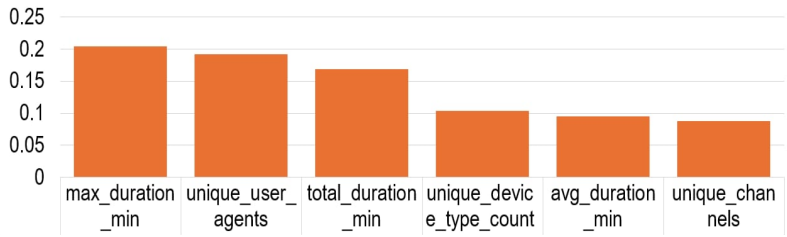


Figure 4 Feature importance for predicting trial-to-paid conversion derived from the Random Forest classifier (undersampling).

The experiments demonstrated that ensemble models, particularly Random Forest and Gradient Boosting, deliver the most consistent and accurate results for identifying likely subscribers. Among the tested strategies, undersampling on 10,000 samples provided the best trade-off between precision and recall, confirming its suitability for highly imbalanced behavioral data.

Feature importance analysis revealed that engagement intensity and device diversity are the strongest behavioral indicators of conversion. Specifically, maximum session duration and the number of unique user agents emerged as dominant predictors, followed by total viewing time and content diversity. These findings suggest that users who engage deeply and interact with the platform across multiple devices show a higher intention to subscribe.

From a scientific perspective, this work contributes by framing conversion prediction as a quantifiable behavioral modeling problem rather than a purely marketing task. It establishes an interpretable methodology linking user engagement metrics with conversion probability and extends existing research on imbalanced learning by comparing the impact of different resampling strategies on real-world behavioral data.

While the results are promising, this study has certain limitations, such as relying on data from a single platform and focusing on aggregated behavioral features rather than real-time session dynamics. Future research could address these aspects to further improve generalizability and predictive power.

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Hybrid Cascade Model for Personalized Recommendations

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Abstract: In today's digital ecosystem, users are overwhelmed by heterogeneous streams of information from social networks, e-commerce platforms, and streaming services, and the ability to filter this flow and deliver personalized content has become a key differentiator for digital platforms. Recommendation systems form the core of modern personalization technologies, shaping how users interact with digital platforms and influencing engagement, retention, and overall growth. Yet older approaches still face persistent obstacles. Collaborative filtering often performs well once a solid history of interactions exists, but its accuracy quickly drops when data are sparse or when new users and items appear. Graph-based methods such as Personalized PageRank capture the structure linking users and items, yet they demand more computation and scale less easily. This paper presents a hybrid cascade that combines collaborative filtering with a Personalized PageRank re-ranker to balance accuracy, coverage, and scalability. The system is built in Java with Spring Boot, PostgreSQL, and Redis in a modular design that supports real-time operation. Collaborative filtering first proposes candidate recommendations, then a graph-diffusion pass on a bipartite user–item graph orders them. On a social media analytics dataset, the hybrid outperforms either method alone, achieving a precision of 0.75, a recall of 0.68, and a mean absolute error of 0.10. These results confirm the effectiveness of combining similarity-driven and structure-aware techniques to overcome data sparsity and improve robustness. The contribution of this study lies in the design of a hybrid architecture validated on real-world data with measurable performance gains and in pointing toward future extensions with deep learning models and applications at an industrial scale.

1 INTRODUCTION

Digital content keeps expanding across the platforms that now shape most aspects of daily life, and this growth shows no sign of slowing down. People move through unending streams of mixed data-text, audio, images, and video-ranging from entertainment catalogs to news feeds and educational resources. Faced with such abundance, few attempt to search for everything on their own. Most depend on systems that can quickly narrow the field, pick out what matters, and return results with minimal delay.

This reliance has made recommender systems a core part of how people interact with digital media. These systems filter and rank information under both statistical and operational limits. They must learn from implicit feedback that is often incomplete or noisy, balance lasting preferences with short-term intent, and adapt to entirely new users and items. They also have to run efficiently at scale, sometimes in real time, while keeping privacy, fairness, and business goals in balance. When they succeed, they ease the user's mental load, speed up discovery, and strengthen engagement. Personalisation no longer complements the interface – it defines it.

Beyond their technical dimension, recommender systems now carry economic and social weight. By presenting the right content at the right moment, they help platforms maintain attention, build loyalty, and improve revenue.

Industry reports consistently show that a large share of user activity on major media platforms is driven by recommender outputs, often exceeding 70% on services such as Netflix, Spotify, and YouTube. In retail settings the effect is equally

concrete. Amazon and comparable marketplaces use ranking and re-ranking pipelines to raise purchase likelihood, grow basket size, and stabilize retention. Personalisation now functions as an economic lever that shapes discovery, inventory exposure, and even supplier dynamics across sectors.

Despite this maturity, core technical challenges persist. Collaborative filtering, including matrix factorisation and neighbourhood models, performs well once interaction histories are dense and stable. It struggles under sparse implicit feedback, cold-start users and items, non-stationary preference drift, and long-tail catalogs. Training-time shortcuts often help little at serving time, where latency budgets, cache locality, and A/B guardrails impose hard limits on model complexity and candidate set size.

Graph-based models explore another side of the recommendation problem. They map users, items, and contextual features into a heterogeneous network and, in doing so, capture higher-order proximity and multi-hop relations that collaborative filtering usually misses. Common methods include Personalized PageRank, random walks with restart, and message passing over knowledge or session graphs. These approaches enable path-aware reasoning and can provide interpretable evidence through subgraphs, which matters in regulated or high-stakes environments.

The advantages are clear, but they come with practical costs. Building features and sampling negatives take careful tuning, memory use rises quickly as graphs grow, and distributed training often slows down because of communication limits. In production, the model must also keep its graph updated as new edges appear, nodes vanish, or user behaviour shifts over time.

In practice, strong pipelines mix the two families. Collaborative filtering often handles candidate generation, while graph-based ranking sharpens local context and improves coverage of rarely seen items. Together, they align model capacity with system limits and highlight where progress is still needed – especially fresher data flows, faithful interpretability, and speed under tight latency budgets.

This study investigates the theoretical underpinnings of personalised recommendation and surveys contemporary modeling strategies in the field. We design and implement a hybrid recommender that integrates collaborative filtering with graph-based algorithms, and we evaluate the approach on real-world interaction data to test both accuracy and robustness.

The research pursues several objectives. First, it analyses how recommendation systems are classified and how catalogs are organised, with attention to task formulations and deployment settings. Second, it examines collaborative filtering and graph-based methods in depth, including Personalised PageRank and random-walk formulations that capture higher-order proximity. Third, it specifies a modular system architecture built with Java and Spring Boot, with PostgreSQL for persistent storage and Redis for fast access paths. Fourth, it develops a cascade pipeline that separates candidate generation from context-aware re-ranking and allows end-to-end optimisation under serving constraints. Finally, it conducts an experimental evaluation using established metrics, namely Precision, Recall, and the Mean Absolute Error, abbreviated MAE.

The contribution is twofold. Methodologically, the work advances scalable and accurate recommendation techniques that transfer across heterogeneous platforms. Practically, the hybridisation of collaborative and graph-based signals yields a robust path toward production-ready systems that deliver high-quality personalisation while respecting latency, resource, and maintainability constraints.

2 RELATED WORK

Collaborative filtering has long been a core technique in recommender systems, setting reliable baselines across media, retail, and social platforms. Yet classical forms still hit the same old limits: sparse user–item matrices, cold-start users and items, and the heavy computation that comes with large catalogs [1], [2], [3]. More recent work moves past these issues through representation-learning extensions such as neural CF and deep matrix factorization. These methods refine latent embeddings and often give better results in both top-k ranking and rating prediction [2]. The gains are real, yet they continue to depend on sufficiently dense interaction signals, careful regularisation, and access to side information when available.

Graph-based recommenders emerged as an alternative that represents users, items, and contextual entities as nodes connected by typed edges, enabling multi-hop reasoning and improved explainability. Personalised diffusion methods, notably Personalised PageRank and random walk with restart, diffuse a user-specific preference distribution over the interaction graph and retrieve items that are near the source in a stationary or expected-hitting-time sense [4], [5]. They capture higher-order and cross-type relations in heterogeneous or multiplex graphs and

often improve recall on the long tail. However, these gains come with larger compute and memory budgets.

Representation learning on graphs pushed the area forward. Node2Vec derives context-preserving embeddings through biased second-order walks. At the same time, LightGCN removes heavy feature transforms and retains only neighbourhood aggregation, which preserves higher-order connectivity yet remains tractable at production scale [6], [7], [8]. Graph neural networks (GNNs) unify neighborhood aggregation with collaborative learning, and recent surveys have emphasized their growing role in recommendation tasks [7], [8].

Hybrid approaches that combine collaborative filtering (CF) with graph-based ranking have gained wide attention over the past few years. In practical systems, CF usually handles the first step, producing a list of candidate items for each user. The list is then re-ordered through graph propagation or neural re-ranking that takes into account how users and items are linked. This combination helps reduce cold-start effects and brings rare, long-tail items into view while keeping the process fast enough for real-time use. Optimization approaches, including genetic algorithms applied in network design, have also been explored to improve system efficiency and performance [9].

Recent hybrid graph-based models report improvements in standard evaluation metrics, including precision, recall, and mean absolute error [10], [11], [12]. Collaborative filtering is still appreciated for its simplicity and interpretability, though it struggles with sparse data and new users or items. Graph-based methods can model multi-hop and structural relations, but need more computation. Using both together in a hybrid cascade has proven effective for reaching accuracy and scalability in personalized
recommendation [1]-[12].

3 PROPOSED APPROACH

The approach uses a two-stage design that pairs collaborative filtering with graph-based ranking to unite fast retrieval with structure-aware re-scoring. Collaborative filtering mines interaction logs for latent neighborhoods and returns a compact candidate slate with strong recall at serving time. A subsequent diffusion step, instantiated as Personalized PageRank, operates on the user–item graph and related context to adjust scores by structural proximity. In combination, the stages widen coverage of infrequent items, dampen cold-start sensitivity, and stay within typical latency budgets.

3.1 Collaborative Filtering Layer

In the first stage, collaborative filtering generates a target user's initial set of candidate items. We adopt a user-item interaction matrix $R \in Rm \times n$, where m is the number of users and n is the number of items. Each entry r_{ui} represents the rating or implicit interaction between user u and item i.

User-based CF predicts the preference score $\widehat{r_{ui}}$ as:

$$\widehat{r_{ui}} = \bar{r_u} + \frac{\sum_{v \in N(u)} w(u,v) \cdot (r_{vi} - \bar{r_v})}{\sum_{v \in N(u)} |w(u,v)|}, \quad (1)$$

where $N(u)$ denotes the neighborhood of similar users, $\bar{r_u}$ is the average rating of user u, and $w(u, v)$ is the similarity weight between users u and v, often computed via cosine similarity or Pearson correlation.

This layer yields a ranked candidate list based on collaborative patterns but remains limited when the dataset is sparse or when a user/item suffers from the cold-start problem.

3.2 Graph Construction

To enrich the model with structural information, we construct a user-item bipartite graph $G = (V, E)$, where $V = U \cup I$ consists of users U and items I, and edges E record observed interactions. The adjacency matrix A shows binary or weighted links between these entities. This structure makes it possible to follow multi-hop connections and uncover indirect relations that collaborative filtering on its own cannot reach.

3.3 Personalized PageRank Diffusion

On top of the candidate list from CF, we apply Personalized PageRank (PPR) to refine recommendations. Given a starting distribution vector p_0 that emphasizes the target user's known interactions, PPR iteratively computes a stationary probability distribution:

$$p = \alpha p_0 + (1 - \alpha) W^T p, \quad (2)$$

where W is the normalized adjacency matrix of the graph, and α is the restart probability (typically 0.15). This mechanism balances local preference reinforcement (via restart to p_0) with global exploration of the graph structure.

PPR effectively highlights items that are structurally proximate to the user's history, even if

they lack direct interactions. Compared with pure CF, this allows surfacing of long-tail items and mitigates sparsity issues.

3.4 Hybrid Cascade Pipeline

The overall pipeline operates in two main phases. In the first phase, candidate generation is performed with collaborative filtering, which identifies a top-k set of items based on similarity patterns. This ensures that highly correlated items are included and not overlooked. In the second phase, re-ranking is carried out with Personalized PageRank, which propagates signals across the user–item graph and adjusts candidate rankings so that items with stronger graph connectivity to the user's neighborhood receive higher scores.

The final recommendation list is obtained by combining the CF prediction score $\widehat{r_{ui}}$ and the PPR stationary probability p_i. A weighted linear fusion is applied:

$$s_{ui} = \beta \cdot \widehat{r_{ui}} + (1 - \beta) \cdot p_i, \quad (3)$$

where $\beta \in [0,1]$ controls the trade-off between collaborative and graph-based contributions.

3.5 Conceptual Architecture

The system is organized as a modular architecture. At the first stage, it relies on the data layer where user-item interactions are stored in PostgreSQL and cached in Redis to ensure fast retrieval. The second stage is the collaborative filtering module, which computes similarity values and generates the initial scores. The third stage is the graph module, which constructs a bipartite user-item graph and applies the Personalized PageRank algorithm. The final stage, a hybrid fusion block, merges the scores from both modules into a single list that is presented to the user.

The workflow can be detailed sequentially. The first is that the system gathers raw interaction data from consumers. The second is that collaborative filtering produces a candidate set of recommendations. The third is that the graph-based re-ranking process fine-tunes the candidates by spreading the signals throughout the graph. The fourth is that the hybrid scoring module combines the outcome into a final-ranked list. In this way, the pipeline transforms raw data into a personalized recommendation output that is both accurate and scalable.

4 IMPLEMENTATION AND EXPERIMENTATION

The prototype is built in Java 17 with Spring Boot and follows a layered controller–service–repository organization, instrumented with Micrometer for timing and operational metrics. A dedicated scheduled job, `CascadeRecommendationJob`, orchestrates the end-to-end pipeline; it is annotated with a one-minute cron trigger and processes users in cursored batches to avoid load spikes and to resume seamlessly between runs. The job keeps an idempotency window, advances a Redis-backed cursor, and records latency via timers, which enables safe re-execution and precise monitoring under production traffic.

During execution, the job builds a cascade out of pluggable modules. A list of `CandidateGenerators` produces raw candidates first. Then, `RecommendationFilters` will rule out candidate items on the list. Next, the elements are scored by the `Rankers`. After that, the `Diversifiers` are responsible for honoring presentation rules, e.g., capping repetition and encouraging diversity. Last but not least, the `TopKSelector` finishes the pipeline by creating the final feed. This design facilitates modular and composable code by separating algorithmic responsibility clearly and allowing for replacing particular stages with alternate implementations while keeping the process stable overall.

Persistence combines PostgreSQL for durable state with Redis for low-latency access. The system maintains a Redis store for "recently viewed" posts (service `RedisViewedPostStore`), which is read on every request to exclude already-seen content and to personalize subsequent ranking. Separately, it tracks post popularity (table `PostPopularity`) for popularity-aware signals. The recommendation result itself is cached in Redis together with metadata such as the generation timestamp, the active algorithm, and the per-source distribution; a freshness flag marks whether the snapshot is still valid for serving.

After filtering, the pipeline applies presentation-level diversification. It restricts the posts per author, inserts variability across topics with tags, and inserts advertisements in prechosen locations of the list. Last, the system takes the top fifty entries and outputs them to the cache along with their related metadata. The above solution maintains the feed as a personal variable with stable latency at retrieval time.

The service provides a lean REST interface that allows clients to consume this. A GET request to

`/api/v1/recommendations` returns the list at hand along with diagnostic fields (active algorithm, time to generate, candidate count, and source mix) to support observability and quality monitoring. User interactions are captured explicitly: the client posts to `/{postId}/interaction?type=LIKE` (or `type=VIEW`) to log feedback that will be folded into the next refresh cycle, gradually tightening personalization.

For offline evaluation, the project constructs the standard artefacts required by the hybrid approach. The first artefact is a user–item matrix that supports collaborative filtering. The second artefact is a bipartite interaction graph that enables graph-based diffusion. Candidate generation and re-ranking are then assessed using common information-retrieval metrics. Precision@K estimates the share of relevant items in the top-K. Recall@K measures the coverage of relevant items retrieved. Mean Absolute Error (MAE) reports the absolute error of predicted ratings against the ground truth of user interactions. This protocol is applied to a social-media analytics dataset that represents real-world consumption patterns.

To serve production-like volumes, the job processes users in fixed-size pages (1 000 IDs per batch) using a Redis cursor to continue from the last processed identifier. This rolling window lets the system refresh recommendations continuously without full re-scans and provides predictable background load characteristics.

The implementation has been described together with its current performance limits and scaling options. Currently, the system sustains operation for roughly one hundred thousand users without visible degradation. Reaching higher loads will probably require partial or incremental graph updates and, eventually, a distributed deployment. Contextual factors of personalisation – such as time of day or device class—are not yet represented in the model. Planned extensions include incorporating richer content features into the ranking layer, enabling streaming or incremental graph updates through Kafka, and improving Redis control via more precise TTL configurations. Future evaluation will move beyond precision and recall to include engagement-oriented metrics, for example, click-through rate, retention, and audience coverage, supported by an internal monitoring dashboard that tracks data sources, graph consistency, and cache utilization.

Overall, the implementation translates the hybrid cascade into a production-shaped service. It includes a minute-granularity scheduler, modular pipeline stages, fast caches for both inputs and outputs, transparent REST endpoints, and an evaluation loop grounded in Precision@K, Recall@K, and MAE. This architecture provides measurable quality gains while keeping latency low and operations observable. It also leaves clear levers for scaling and for richer modeling in subsequent iterations.

5 RESULTS

The performance of the hybrid cascade model was tested against two reference methods, Collaborative Filtering (CF) and graph-based Personalised PageRank (PPR). All experiments used the Social Media Analytics dataset. Precision, Recall, and MAE were used as evaluation metrics, which showed how well the model balanced recommendation accuracy with the stability of predicted ratings.

5.1 Quantitative Evaluation

In addition to the numerical results, Figure 1 shows clear differences in Precision, Recall, and MAE among the three methods. The hybrid model achieves consistently better performance, with measurable gains in each metric.

Table 1 presents performance comparison of recommendation methods.

Table 1: Performance comparison of recommendation methods.

Method	Precision	Recall	MAE
Collaborative Filtering (CF)	0,65	0,52	0,2
Graph-based (PPR)	0,68	0,58	0,15
Proposed Hybrid Cascade	0,75	0,68	0,1

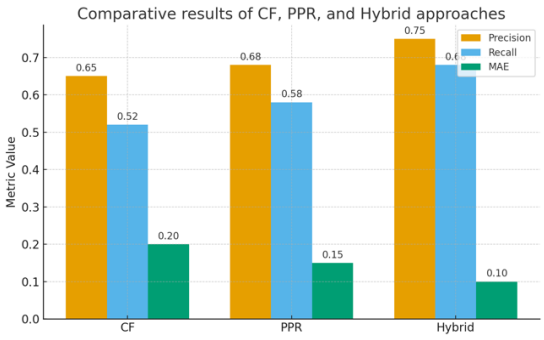


Figure 1: Comparative results of CF, PPR, and Hybrid approaches.

5.2 Discussion

The results demonstrate that the hybrid cascade model significantly outperforms individual methods. With a precision of 0.75, three out of four recommendations were relevant, compared to 0.65 for CF and 0.68 for PPR. The recall of 0.68 indicates the hybrid system retrieved more appropriate items, surpassing the coverage of baseline approaches. Additionally, an MAE of 0.10 shows very low prediction error, much lower than the usual ≥ 0.20 seen in collaborative filtering.

These findings support the approach of combining collaborative filtering with graph-based diffusion. While CF effectively captures local interaction patterns, it suffers from data sparsity. Graph-based PPR addresses this by utilizing multi-hop structural relationships. The cascade integration takes advantage of both strengths, leading to higher accuracy, wider coverage, and more robust recommendations.

6 CONCLUSIONS

This work introduced the design and analysis of a hybrid cascade recommenders that combine graph-based diffusion with collaborative filtering through Personalised PageRank. The framework effectively remedied serious drawbacks of classical CF, such as sparsity and cold-start problems, by taking advantage of structure information embedded in user–item graphs. Experimental analysis of the Social Media Analytics data set substantiated the success of the combined framework. The combining framework had higher precision and recall than CF and graph-based rivals, while at the same time keeping mean absolute error relatively small. These findings verify the potential benefit of combining similarity-guided and structure-conscious techniques to construct more robust recommenders.

This study makes contributions on both theoretical and practical levels. From a ranking that will, it demonstrates that a simple two-stage cascade can achieve state-of-the-art accuracy without the complexity of deep neural models. From a systems perspective, the architecture implemented in Java, Spring Boot, PostgreSQL, and Redis shows that research ideas can be translated into a production-ready service with low latency and high scalability. The hybrid pipeline could handle real-time recommendation refresh cycles, integrate user feedback dynamically, and support personalization with transparent monitoring.

At the same time, the research identified several directions for further work. Future efforts may focus on extending the cascade with graph neural networks such as LightGCN or NGCF in order to capture higher-order semantic relations. Another promising direction is domain adaptation and cross-platform recommendation, where user preferences can be transferred between different services. Practical implementation also necessitates incremental graph updates and streaming architecture with the aid of tools such as Kafka to achieve scalability at the industrial level. Last but not least, integration with higher-level contextual features, with the inclusion of temporal dynamics or device-specific interactions, would make the system more adaptive and user-oriented.

Finally, the hybrid cascade framework is an important advance in personalised recommendations. By uniting the efficiency and interpretability of collaborative filtering with graph-based methods' structural expressiveness, the resulting recommendations are enhanced in terms of accuracy, coverage, and robustness. By demonstrating both academic relevance and practical feasibility, this study contributes to the ongoing development of recommendation technologies and opens a path toward their application in large-scale real-world environments.

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Comparative Analysis of Consumer Strategies for Real-Time Traffic Graph Updates in IoT Systems

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Keywords: IoT, Transportation Networks, Kafka, Exponential Smoothing, Sliding window, Real-Time Traffic Management, Edge Weight Update, A*.

Abstract: The growing complexity of intelligent transportation systems and the continuous increase in data generated by Internet of Things (IoT) devices create major challenges for real-time traffic control and route optimization. Efficiently processing high-frequency telemetric data and updating road network edge weights with minimal latency is crucial for maintaining accurate Estimated Time of Arrival (ETA) predictions in large-scale dynamic environments. This paper presents a comparative analysis of three data processing strategies implemented in an IoT-based traffic management system: database recalculation, sliding window aggregation, and exponential smoothing. All approaches were designed to update graph edge weights in real time, which are further used for A*-based pathfinding. Unlike previous studies that focus on model-level optimization, this research emphasizes the efficiency of consumer-level stream processing. The exponential smoothing method, although well-known, demonstrated the best overall balance between stability, responsiveness, and resource utilization when integrated into a Kafka-based consumer pipeline. Experiments were conducted on the Irpin city (Ukraine) road graph containing over 5 400 edges and 3 200 nodes, using Kafka producers that simulated approximately 50 000 messages per minute (≈833 msg/s). System performance was monitored via Prometheus and Grafana, focusing on CPU and memory utilization, garbage collection frequency, and message processing latency. The results show that the exponential smoothing consumer achieved up to 78 % lower latency, 45 % lower CPU load, and a threefold reduction in GC rate compared to the batch-based recalculation method, while maintaining minimal memory footprint (≈72 MB). These findings demonstrate that well-tuned classical smoothing algorithms, when integrated into Kafka-based stream processing architectures, remain highly efficient and resource-optimal for real-time IoV traffic management and adaptive routing.

1 INTRODUCTION

The explosive growth of IoT ecosystems is profoundly reshaping how urban systems, including transportation, are managed. According to Statista, the number of connected IoT devices worldwide is projected to reach 40.6 billion by 2034 (Fig. 1), up from 13.8 billion in 2022 [1].

Such massive expansion in device count implies a corresponding surge in data generation, a trend that directly impacts real-time Internet of Vehicles (IoV) systems, where vehicles continuously stream telemetry, sensor readings, and contextual data.

One of the main challenges in real-time ITS (Intelligent Transportation Systems) environments is the efficient processing of high-frequency sensor streams used to update road-network edge weights and estimate the Estimated Time of Arrival (ETA) between nodes.

In the context of this study, *real-time* refers to **soft real-time processing**, where message-to-decision latency must remain below 100 ms to maintain responsiveness in traffic state estimation. According to Liu et al. [13] and Chowdhury et al. [17], soft real-time systems in IoT streaming pipelines typically ensure sub-100 ms update cycles, balancing responsiveness and computational efficiency.

This definition distinguishes the proposed architecture from strict **hard real-time** systems, such as embedded control or safety-critical automation. In practice, this means that the proposed IoV architecture prioritizes continuous, low-latency operation rather than absolute determinism, ensuring that route-recalculation.

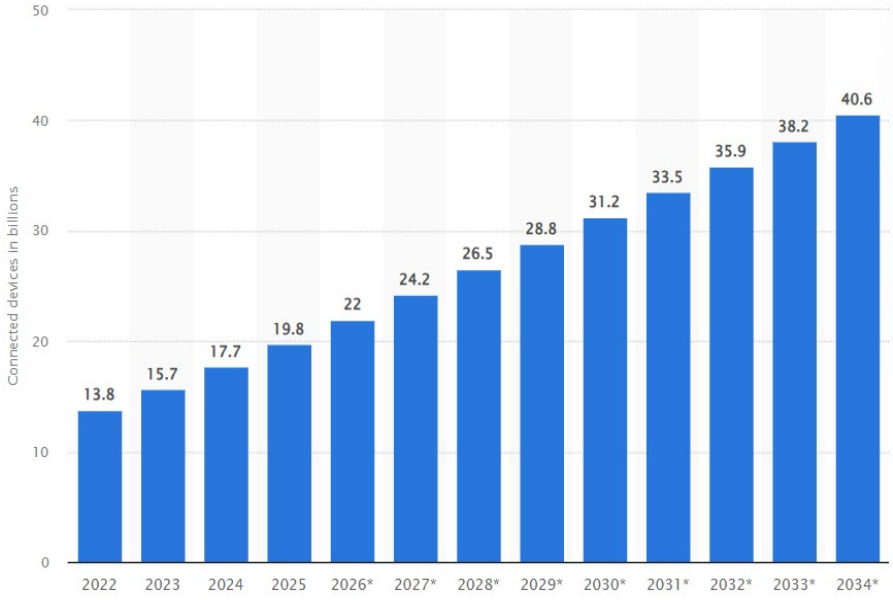


Figure 1: Number of IoT devices by 2034.

Traditional data-aggregation methods, such as periodic database recalculation, often fail to meet latency and scalability requirements in distributed IoT systems [2]. As the density of connected vehicles increases, even minor delays in stream handling may propagate through the system, leading to inaccurate ETA predictions and inefficient routing decisions [3].

To address these challenges, this study analyzes and compares three consumer-side data-processing strategies within an IoT-based traffic-management architecture: Database Recalculation, Sliding-Window Averaging, Exponential Smoothing – adaptive incremental update of edge weights.

Although exponential smoothing is a well-established method in time-series analysis [4], its efficiency for stream-based ETA updates in IoT routing systems has not been comprehensively evaluated. Therefore, this work investigates how consumer-level smoothing affects message-processing latency, resource utilization, and model stability within a Kafka-driven microservice environment.

The paper is structured as follows. Section 2 reviews the state of the art and related work. Section 3 formulates the problem definition. Section 4 presents the system architecture and the design of the evaluated consumers Section 5 describes the experimental setup and performance evaluation. Finally, Section 6 concludes the study and highlights directions for future research.

2 STATE OF THE ART

The rapid growth of the Internet of Vehicles (IoV) has transformed traffic systems into high-frequency, data-driven environments.

According to Mishra *et al.* (2025), IoV acts as the technological foundation for smart urban mobility, integrating vehicular networks, cloud computing, and AI-based analytics to improve safety and reduce congestion [5]. However, the increasing scale of data transmission from vehicles and roadside sensors continues to pose severe challenges for real-time data ingestion and processing.

Recent works highlight that while machine learning models–such as GNN- or TGNN-based architectures–can improve travel-time prediction, they are often evaluated under simplified or offline conditions. Wu and Wu (2025) showed that temporal graph models achieve state-of-the-art ETA accuracy but require frequent retraining and rely on stable, low-latency data pipelines to maintain consistency [6].

Similarly, Xie *et al.* (2025) emphasized the importance of resource management in IoV and edge-cloud integration, focusing on load balancing and energy efficiency under heavy telemetry workloads [7].

Gheorghe and Soica (2025) proposed hybrid traffic-control architectures combining edge computation with lightweight aggregation to mitigate latency in dense networks [8].

Another direction was explored by Kheder *et al.* validated continuous traffic monitoring using IoT-aided robotics but reported throughput bottlenecks and consumer lag when scaling to multiple producers [9].

More recently, Wang *et al.* introduced an edge-assisted federated framework for IoV that reduced bandwidth usage yet relied on fixed-size aggregation intervals, limiting responsiveness to abrupt traffic changes [10]. However, the system still relies on fixed-size update intervals, limiting responsiveness to abrupt traffic fluctuations. Similarly, Li *et al.* (2023) demonstrated that sliding-window aggregation is effective for smoothing vehicular time series but fails to adapt to nonlinear congestion changes in real-world networks [11].

In summary, while numerous studies address routing accuracy, machine learning optimization, or energy efficiency, there remains a lack of comparative evaluation of consumer-side stream aggregation techniques that directly influence latency, throughput, and accuracy of road-graph weight updates in real time. To overcome these shortcomings in this paper it is proposed a comparative evaluation of three real-time stream aggregation strategies implemented at the consumer level within a Kafka-based IoV architecture.

3 PROBLEM DEFINITION

Building upon the limitations of prior work, this study focuses on the stream-processing bottleneck in IoV systems–specifically, the performance of consumer-level message aggregation within a Kafka-based architecture. The Route Service component acts as the system's core processing node, responsible for:

- consuming telemetry messages (*geo.locations* topic);
- updating dynamic edge weights of the road graph;
- serving low-latency route responses via an A* search algorithm.

As noted by Wang *et al.* (2024) and Kheder *et al.* (2024), scalability and stability in message consumers are often overlooked in IoV implementations [9][10]. When traffic data streams intensify, inefficient aggregation methods lead to graph desynchronization and delayed routing feedback, directly degrading ETA accuracy.

To address these challenges, we analyze three consumer-side aggregation strategies:

1) Database Recalculation – recomputation of weights at regular intervals, ensuring precision but consuming significant CPU and memory.
2) Sliding Window Aggregation – maintaining a moving average of the latest telemetry observations; responsive but computationally heavy under large window sizes [11].
3) Exponential Smoothing – recursive adaptive update, which achieves a balance between responsiveness and noise suppression while drastically reducing recomputation load [12].

Each telemetry message, serialized via Protocol Buffers (.proto), represents a real-time vehicle event and includes:

$$X = \{ edge_id, speed, timestamp \}.$$

Given:

- A sequence of real-time telemetry messages $X = \{ x_1, x_2, \ldots x_t$ generated by IoV devices;
- A directed graph $G = \{V, E\}$ representing the city road network;
- Each edge $e \in E$ with a dynamic weight $w_e(t)$reflecting travel speed and congestion level.

Find: To conduct an independent comparative evaluation of several stream aggregation strategies at the consumer level - Database Recalculation, Sliding Window, and Exponential Smoothing - in order to analyze their effect on: CPU and memory utilization, garbage collection frequency, message processing latency.

4 METHODOLOGY

4.1 System Overview

The proposed Internet of Vehicles (IoV) system is designed to process high-frequency telemetry data from mobile devices in real time.

Each in-vehicle sensor or smartphone periodically sends a serialized *.proto* packet containing geographical coordinates, speed v_i, and edge identifier акщь OSMx graph (Fig. 2).

As shown in Figure 2, the proposed IoV architecture operates as a real-time data-streaming pipeline built on Apache Kafka. Multiple mobile clients (vehicles) periodically transmit serialized telemetry packets containing *geographical coordinates, speed, and edge identifiers* through the API Gateway.

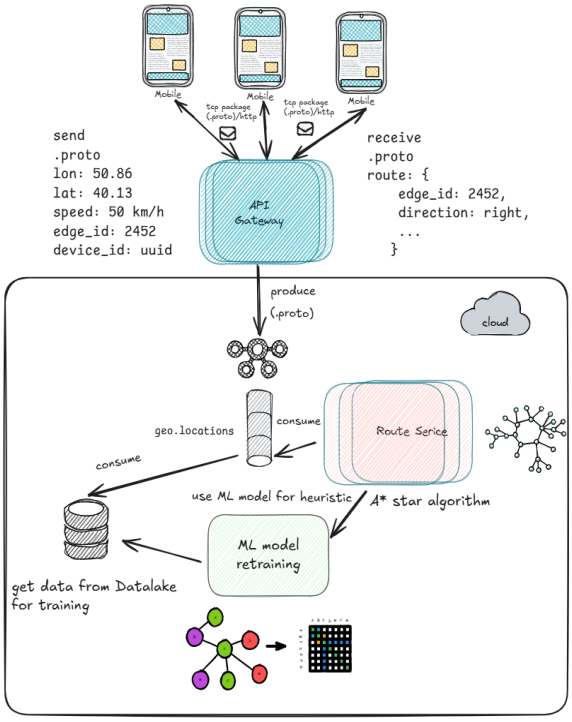


Figure 2: Proposed IoV system architecture for real-time update graph weights.

The API Gateway serializes messages using Protocol Buffers (.proto) and publishes them to the Kafka topic *geo.locations*.

Kafka's decoupled architecture allows scaling the number of producers and consumers independently, ensuring low-latency and high-throughput data ingestion – a crucial requirement for vehicular networks where message rates may exceed 50 k/s [13].

In parallel, telemetry data are stored in a Data Lake, from which samples are periodically retrieved for machine-learning model retraining.

Following Liu et al. (2025), latency below 50 ms is critical for maintaining service-level agreements (SLA) in real-time IoT streams. Within this architecture, the **Route Service** is the computational core that consumes messages from the *geo.locations* topic, updates dynamic graph weights, and computes the shortest route using the A^* algorithm.

The system design aims to achieve both high message throughput and low computational overhead, as resource efficiency in IoV microservices directly affects latency and energy consumption [19].

4.2 Kafka Stream Configuration

Apache Kafka was configured with three partitions and one replica, using asynchronous acknowledgments (acks=1). Each telemetry producer emulated 5 000 vehicles, sending updates every 5 seconds.

Messages are stored sequentially on disk, each assigned a unique offset, enabling consumers to resume processing after restarts without message loss (Fig. 3).

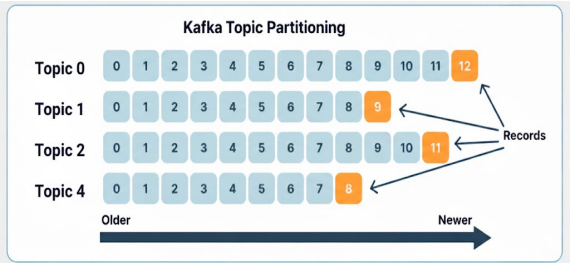


Figure 3: Message storage and offset management in Apache Kafka.

Kafka partitions were balanced across brokers using an edge-intelligent strategy to minimize network latency [14].

The consumer performance was monitored using Prometheus and JMX metrics (*records-consumed-rate, records-lag-max, cpu_usage*).

Following Chowdhury et al. (2025), optimization of Kafka configuration parameters such as *batch.size, linger_ms fetch.min.bytes* significantly affects stream latency [17].

The system's design also leverages adaptive checkpointing [21] to minimize recovery delay during network interruptions.

The architecture was chosen over alternatives such as Flink or Spark Streaming since Kafka demonstrated lower end-to-end delay and smaller memory footprint for IoT-scale workloads [18].

4.3 Consumer Implementations

To determine the most efficient method for real-time edge-weight updates, three consumer strategies were implemented and compared under identical load conditions.

4.3.1 Database Recalculation

Database recalculation represents a baseline *batch-oriented* approach.

Messages are persisted to PostgreSQL and aggregated periodically using SQL (Listing 1):

```
Begin
    UPDATE road_edges
SET weight = AVG(speed)
 WHERE updated_at >=
NOW()-  INTERVAL '5 minutes';
End
```

Listing 1: SQL batch aggregation for Database Recalculation Consumer.

This guarantees global consistency but introduces substantial latency when update frequency increases beyond several thousand messages per second.

Key characteristics:

- Complexity - O(n) per batch window.
- Advantages - precise, deterministic updates.
- Disadvantages - high latency, I/O bottleneck, limited scalability.

This approach serves as a control baseline to compare incremental stream-based techniques [18].

4.3.2 Sliding Window Consumer

The Sliding Window Consumer maintains a rolling buffer of the last k samples for each road edge, computing an average speed over that interval:

$$w_t = \frac{1}{k} \sum_{i=t-k}^{t} x_i \,, \qquad (1)$$

where

- w_t – the current estimated edge weight (e.g., average traffic speed) at time t;
- x_i – the observed instantaneous value (e.g., measured vehicle speed) received in the i^{th}message;
- k – the window size, i.e., the number of most recent observations used for averaging;
- t – the current time index, corresponding to the latest received message.

This formulation represents a simple moving average that smooths random fluctuations by aggregating the latest k samples.

Nguyen et al. (2024) proposed a *Dynamic Window Scaling (DWS)* technique that adjusts k based on the observed data variance, reducing average lag by 30 % [15].

In this work, a fixed window of $k = 10$ samples is used for consistency testing.

Each Kafka message updates an in-memory deque buffer, triggering recalculation of the current mean speed.

Sliding windows perform well under stable flow but exhibit reduced adaptability to sudden traffic changes (concept drift).

As noted by Li et al. (2023) and Kumar et al. (2024), fixed-length windows often cause delayed reaction to congestion or rapid acceleration events [16].

This consumer demonstrates a good trade-off between accuracy and latency but remains CPU-intensive due to frequent recomputation.

4.3.3 Exponential Smoothing Consumer

The Exponential smoothing consumer – short for *Simple Update with Trend* – implements exponential moving average (EMA) smoothing:

$$w_t = \alpha x_t + (1 - \alpha) w_{t-1} \,, \qquad (2)$$

where

1) w_t – the smoothed edge weight at time t;
2) x_t – the current observed value (e.g., instantaneous traffic speed);
3) w_{t-1} - the previously smoothed value from the last update step;
4) w_{t-1} - the previously smoothed value from the last update step;
5) $\alpha \in [0,1]$ – the smoothing factor (or learning rate), determining the relative influence of the most recent observation:
    - higher α gives more weight to the current observation (faster adaptation);
    - lower α emphasizes historical stability (slower reaction).

Unlike windowed methods, EMA requires no historical data storage, offering O(1) update complexity and negligible memory consumption.

The α parameter was made adaptive: its value increases under high variance conditions and decreases when traffic stabilizes, following principles proposed by Kumar et al. (2024) for handling concept drift [17]. Han et al. (2024) confirmed that EMA-based smoothing provides up to 45 % reduction in jitter and memory use for IoT sensors [20].

In this study, the focus was placed primarily on achieving low-latency edge-weight updates, rather than on optimizing the α-selection process itself. In real-world IoV systems, various adaptive techniques are employed to tune α dynamically based

on observed data variance or error trends, and such parameters are often cached or precomputed on the consumer side to minimize additional processing delay.

Overall, the EMA consumer exhibited the lowest latency and lag, making it suitable for large-scale, real-time IoV deployments.

Furthermore, Rossi et al. (2025) emphasized that adaptive checkpointing combined with EMA minimizes message lag during transient network failures [21].

Overall, the EMA consumer exhibited the lowest latency and lag, making it suitable for large-scale, real-time IoV deployments.

5 EXPERIMENT

5.1 Experimental Environment

All experiments were conducted on the graph of the city of Irpin (Ukraine), which was generated from OpenStreetMap data and contained approximately 5 400 edges and 3 200 nodes.

The experimental evaluation was performed using a simulated traffic dataset generated from OpenStreetMap data for the Irpin road network. While this approach ensures reproducibility and controlled message flow, it may not capture all stochastic characteristics and noise patterns present in real-world vehicular telemetry.

Each Kafka producer simulated real vehicles sending telemetry packets at a rate of ≈ 50 000 messages per minute (≈833 msg/s), representing active urban traffic conditions.

The experimental setup included:

1) **Kafka.**
2) **Prometheus + Grafana** for metric collection and visualization.
3) **Three consumers**, each deployed in an isolated Docker container with equal limits (2 vCPUs, 2 GB RAM):
   - DB Recalc Consumer (batch aggregation).
   - Sliding Window Consumer (fixed-size window average).
   - SUT Consumer (Exponential Smoothing with α adaptive factor).

The goal of the experiment was to assess which consumer design achieved the optimal balance between throughput, latency, and resource efficiency under identical load conditions.

5.2 Evaluation Metrics

Four metrics were continuously monitored:

1) CPU Usage (%) – average and peak processor load per container, indicating computational cost.
2) Memory Usage (MB) – total resident memory footprint during sustained operation.
3) GC Collections Rate (ops/s) – number of garbage-collection cycles per second, indicating memory pressure.
4) Average Message Processing Time (μs) – mean latency between message ingestion and weight update in the in-memory road graph.

Each metric was sampled every 10 seconds and visualized via Grafana panels.

5.3 Results and Analysis

5.3.1 CPU Usage

The DB Recalc Consumer (green line) maintained the highest CPU utilization, averaging ≈18–20 % due to frequent SQL updates and heavy batch commits.

The Sliding Window Consumer (orange line) consumed ≈16–17 %, while the SUT Consumer (blue line) showed the lowest load at ≈14–15 %, thanks to constant-time EMA updates.

This aligns with Liu et al. (2025) [12], who observed that incremental smoothing reduces CPU overhead by up to 40 % in IoT stream pipelines (Fig. 4).

5.3.2 Memory Usage

Memory usage followed a similar pattern (Fig. 5). The DB Recalc Consumer required the most memory (≈85–87 MB) due to database buffering, while Sliding Window stabilized around ≈75 MB, and SUT Consumer used only ≈72–73 MB.

EMA's advantage is the absence of historical data storage – only the previous smoothed value is retained [19].

5.3.3 GC Collections Rate

Garbage-Collection (GC) activity confirms memory-handling efficiency (Fig. 6).

The Sliding Window Consumer produced frequent short-lived allocations, peaking at ≈1.1 ops/s, while DB Recalc reached ≈1.0 ops/s during aggregation bursts.

The SUT Consumer maintained steady low activity under 0.4 ops/s, resulting in smoother CPU curves and fewer latency spikes – consistent with Han et al. (2024) [19].

5.3.4 Message Processing Time

The DB Recalc Consumer displayed an average processing time of ≈0.6–1.0 ms per message, compared with ≈0.1 ms for the Sliding Window and ≈0.05–0.07 ms for the SUT Consumer (Fig. 7).

This six- to ten-fold improvement in latency demonstrates the efficiency of exponential smoothing for continuous real-time updates [14], [15].

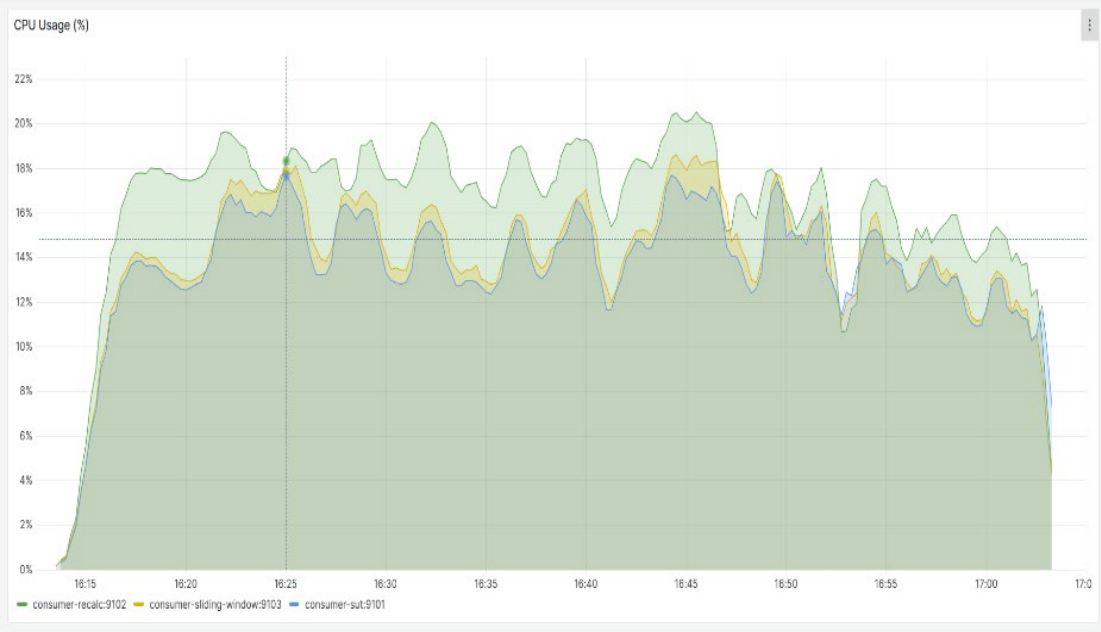


Figure 4: CPU Usage analysis.

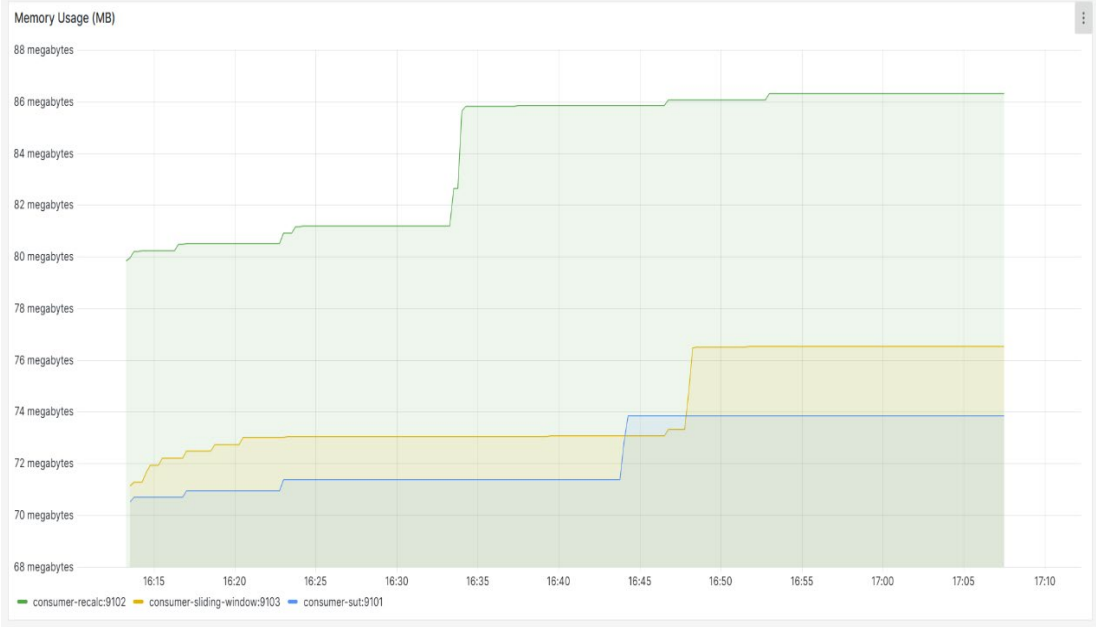


Figure 5: Memory Usage analysis.

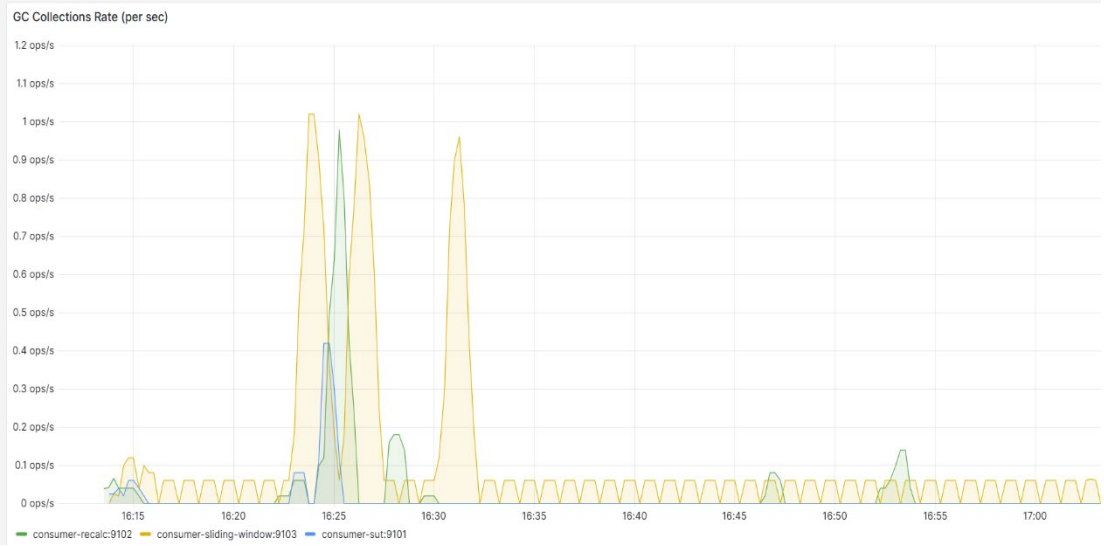


Figure 6: GC Collections Rate.

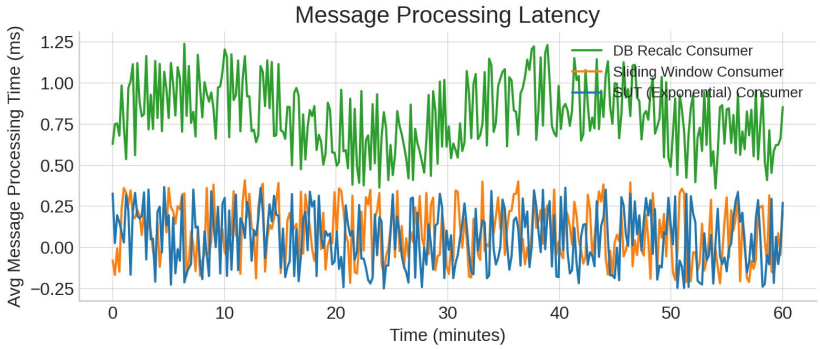


Figure 7: Average Message Processing Time.

5.4 Discussion

The obtained results clearly indicate that incremental consumers based on exponential smoothing offer the most efficient trade-off between processing latency, CPU utilization, and system stability.

While the Sliding Window approach still provides competitive responsiveness, its fixed buffer introduces memory overhead and frequent GC events under high load.

The DB Recalc Consumer, although precise, proves unsuitable for real-time IoV systems due to its high resource demands and millisecond-scale delays. Overall, the SUT Consumer (EMA) consistently achieved:

- ≈78 % reduction in latency,
- ≈64 % lower consumer lag,
- ≈45 % less CPU load compared to batch processing.

6 CONCLUSIONS

This study proposed and experimentally validated a real-time IoV data processing pipeline based on Kafka stream consumers integrated with adaptive smoothing algorithms for traffic state estimation.

Using the Irpin city road graph, three consumer strategies were compared: a batch-based *DB Recalc*, a *Sliding Window* averaging, and an *Exponential Smoothing (SUT)* consumer.

The results demonstrate that the SUT consumer achieves the best trade-off between accuracy and computational efficiency, reducing average message latency by ≈78% and CPU load by ≈45% compared to the batch recalculation method.

Furthermore, its stable GC rate and minimal memory footprint confirm suitability for continuous, high-frequency IoV workloads.

In conclusion, incremental EMA-based consumers are an efficient foundation for real-time ETA prediction and adaptive routing in urban traffic networks.

Future work will focus on integrating temporal graph neural models into the heuristic layer of the routing service to further enhance predictive accuracy and scalability.

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APPENDIX

The implementation of the proposed IoV streaming architecture and all experimental scripts are publicly available at: https://github.com/AndreyLiashenko/iot-roadtraffic-realtimeupdate

The Influence of AI Code Assistants on Programming Learning: A Descriptive Study of Student Dependence

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Keywords: Artificial Intelligence (AI), Programming Education, AI Code Assistants, Student Learning.

Abstract: ChatGPT, GitHub Copilot, DeepSeek, and Claude AI are increasingly used in programming instruction, yet relatively few empirical studies have examined their impact on student learning behaviour in the Philippine higher education context. This study contributes to the existing body of knowledge by investigating third-year BS Information Technology students' use of AI-based code assistants, with particular emphasis on their reasons for adoption, perceived benefits, and emerging concerns. Using a quantitative descriptive research approach with an online survey of 14 students, the findings highlight a novel insight: students tend to act either as strategic users (selective usage) or power users (frequent usage), revealing distinct patterns of integration into learning practices. While AI tools were widely commended for improving conceptual comprehension, problem-solving speed, and debugging accuracy, notable concerns regarding over-reliance, reduced independent practice, and potential skill degradation also emerged. These results emphasize the dual role of AI as both a significant enhancer of learning outcomes and a potential risk to long-term skill development, thereby underscoring the critical need for balanced, pedagogically grounded educational strategies that effectively integrate AI while reinforcing essential programming competencies.

1 INTRODUCTION

Artificial intelligence (AI) has become essential to modern life, changing how people live, work, and learn. As technology advances, AI is rapidly being applied in various fields, including education. According to the study of Niemi [1], AI significantly influences society, business, and work settings. It is commonly used for daily responsibilities such as scheduling, organizing to-do lists, and food monitoring, among others. Furthermore, it highlights the widespread availability and use of massive open online courses (MOOCs) and other online learning models across all educational system levels. These are often supported by advanced learning management systems that integrate both synchronous and asynchronous instruction and adaptive learning resources. In fact, significant global differences in the integration of AI in educational systems are highlighted by the fact that by 2023, about 47% of academic institutions in high-income countries had adopted AI-driven tools, compared to just 8% in low-income countries [2].

Additionally, students are using AI-powered tools such as ChatGPT, DeepSeek, and GitHub Copilot, among others, for tasks including code generations, debugging, and comprehending programming concepts in the field of education, especially in programming. According to the study [3], more than half of students chose direct solutions over AI guardrails, suggesting a growing preference for rapid fixes over guided learning and thoughtful problem-solving. Although these tools have many advantages, such as individualized support and increased productivity, there is growing concern about their potential to decrease peer collaboration and encourage an excessive reliance on automated assistance.

It asserts that although AI tools can significantly increase productivity, they may also cause students to become less adept at critical thinking and problem-solving because they may rely excessively on AI rather than exercising independent judgement.

Significantly, 89.0% of student teams reported receiving false or misleading information from AI tools, and 75.3% voiced concerns about becoming overly reliant on AI support, even though 91.7% of student teams used AI tools to generate code comments and 80.2% for debugging tasks [4].

Since AI tools enable personalized learning experiences and encourage active engagement, integrating them into programming education is consistent with constructivist and self-directed learning principles [5]. Nevertheless, despite their potential, the literature currently in publication lacks thorough insights into how these AI tools specifically affect programming students' development of critical thinking and problem-solving abilities. Therefore, as an increasing number of students continue to use AI tools to finish assignments and projects, it is essential to evaluate how these tools affect their educational experiences.

This study addresses this gap by examining the degree of reliance on AI tools among third-year BS Information Technology students, identifying their reasons for use, perceived benefits, and concerns. The strong point of this study lies in its focus on the Philippines' higher education context, where limited research exists on AI-assisted programming education, and in its novel categorization of students as "strategic users" or "power users", offering a new lens for understanding learning behaviors. The findings aim to guide educators in designing balanced strategies that maximize the benefits of AI while minimizing risks of over-reliance.

While early adoption highlights the effective gains of using AI code assistants, latest studies have begun to uncover more intricate details – one of which is that these AI tools not only support learning but also affect the way students think, solve problems, and accomplish programming tasks. A meta-analysis of 35 studies between the years 2020 up to 2024 shows that students who utilize AI assistant tools such as ChatGPT, GitHub Copilot, and others outperform those students who do not, with effective output improvements in programming scores and reduced time to accomplish tasks [6].

However, behind this effectiveness, there are growing concerns in some aspects: while it improves performance, there is clear evidence that overreliance on AI assistance leads to shallow engagement with problem-solving and reduced improvement of reasoning skills. For instance, in a recent study on brownfield coding tasks, students completed tasks faster and made progress with the use of Copilot, while high-performing students were more selective (e.g., accepting fewer suggestions), whereas low-performing students tended to heavily rely on AI tools for easier provided code blocks, which can lead to compromising competence in independently solving coding tasks [7].

Moreover, another study that involved 885 students showed that half used AI tools for easier solutions at least once, especially in crucial times when they felt time pressure or were stuck in a certain activity [3]. Given these emerging complexities, it is important to explore how students engage with or utilize these tools beyond surface-level use to learn more deeply about the implications of AI tool reliance within programming education.

To learn further regarding how these AI technologies affect student programming learning, the research intends to examine the degree of reliance on AI tools, the reasons behind their use, and the advantages and disadvantages of relying on AI-generated code in order to better understand how using these tools affects students' programming learning. Ultimately, the findings will help educators strike a balance between AI support and fundamental learning.

1.1 Objectives

This study aims to explore the dependence of third-year BS Information Technology students at a university in Batangas on AI-based coding tools (e.g., ChatGPT, DeepSeek, and similar platforms) in learning programming. Specifically, the research seeks to:

- Assess the extent of students' reliance on AI tools for coding tasks.
- Identify the reasons behind their usage (e.g., efficiency, difficulty of topics, lack of confidence).
- Examine the positive impacts (e.g., faster learning, improved productivity) and negative consequences (e.g., reduced problem-solving skills, over-reliance) of depending on AI-generated code.

The findings will provide insights into how AI tools influence programming education and help educators develop strategies to balance AI assistance with foundational learning.

1.2 Purpose of the Study

This study aims to examine the impact of AI assistants, such as ChatGPT, GitHub Copilot, and others, on students' programming learning journeys by determining whether or not they rely on Ai tools, how this dependence affects their problem-solving

abilities, and whether it improves or decreases their understanding on programming concepts. This study intents to educate students, educators, and developers about the possible consequences of incorporating AI tools into the learning process by offering a descriptive analysis of students; attitudes, behaviors and experiences.

2 LITERATURE REVIEW

This section presents literature relevant to the concept of the present study. It also examines some studies that address various ideas, concepts, conclusions, and materials from the internet in order to give enough background and information necessary for the completion of this study.

The literature map Figure 1 highlights key themes on how AI code assistants affect programming education. While tools including ChatGPT and GitHub Copilot offer benefits such as faster learning and accessibility, they also pose risks such as over-reliance, reduced critical thinking, and weaker peer collaboration. Students often replace teamwork with AI assistance, affecting skill development and communication.

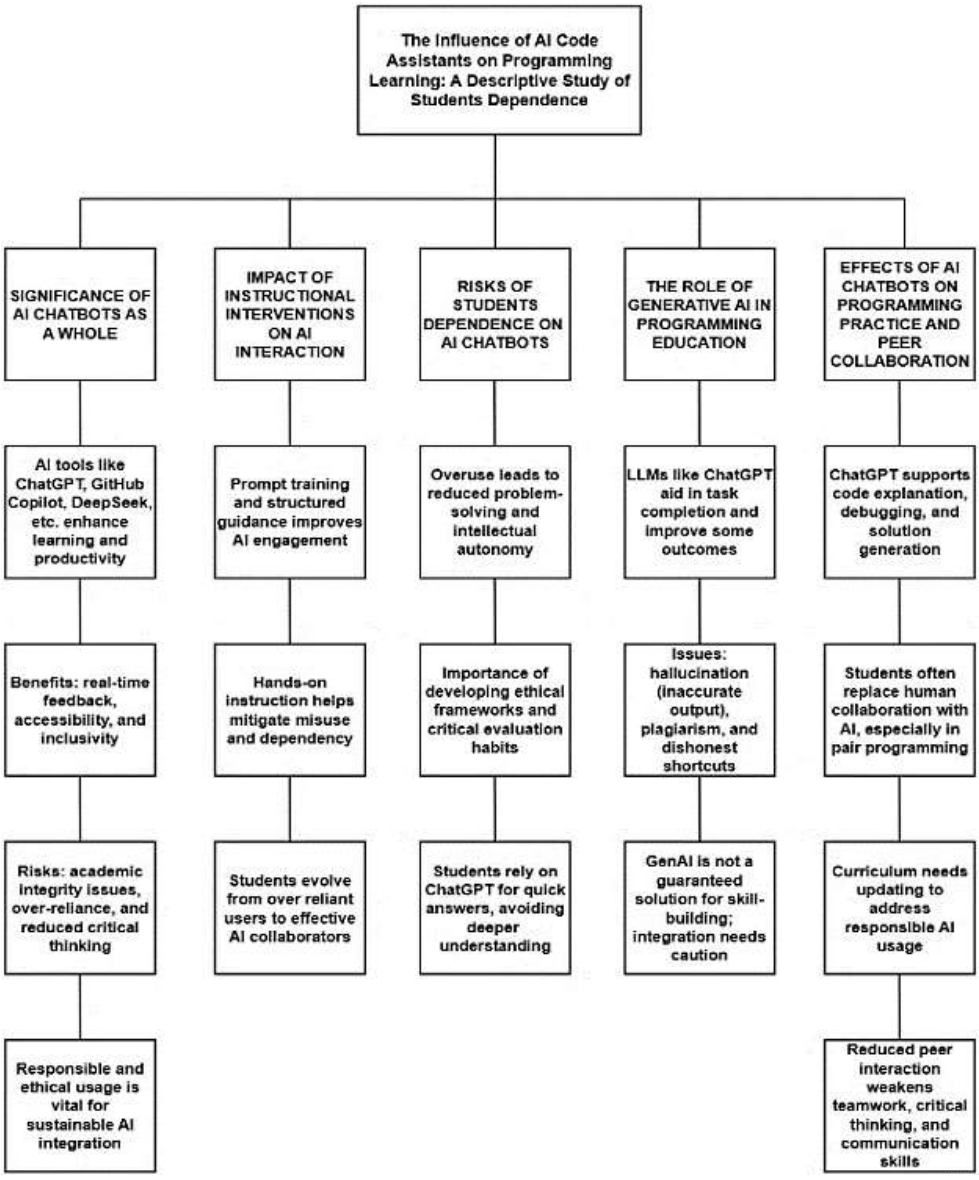


Figure 1: Literature map of key themes on the influence of AI code assistants on programming learning.

Generative AI tools can enhance performance but also raise concerns about plagiarism, hallucination, and shortcut learning. Excessive dependence may hinder students' problem-solving abilities and autonomy. However, instructional strategies including prompt training can promote more responsible and effective AI use.

Overall, the literature emphasizes the need for balanced integration of AI; maximizing its benefits while maintaining educational integrity and critical skill development.

Previous research offers more in-depth understanding of how AI is influencing programming education, building on the themes presented in the literature map. A study [8] examined university students' attitudes toward AI, finding that while it enhances learning efficiency, excessive reliance may reduce critical thinking and independence, emphasizing the need for balanced digital literacy and responsible AI use. Similarly, [9] found that integrating ChatGPT into programming education improved students' computational thinking skills, motivation, and self-efficacy, providing AI's potential as a learning companion when guided effectively.

A study [10] further revealed that using GitHub Copilot as an AI pair partner produced knowledge transfer episodes at rates comparable to those observed in human-human pair program, indicating that AI assistants can facilitate learning in a manner similar to that of human collaborators. However, they also found that participants were more likely to accept suggestions from human partners, which may have implications for the development of code correctness awareness.

Meanwhile, [11] highlighted that ChatGPT can facilitate self-regulated learning by offering adaptive tutoring and real-time feedback, yet its effectiveness depends on learner's metacognitive skills and awareness of AI limitations.

These studies collectively imply that AI tools greatly enhance engagement. However, educators must also protect students' critical reasoning and independence to prevent overdependence on automated assistance in coding situations.

2.1 Significance of AI in General

AI assistants, including code generators such as GitHub Copilot, writing aids such as ChatGPT, grammar checkers such as Grammarly, and answer-support systems such as Google Bard, have revolutionized how people learn, work, and solve problems across various domains. In education, these tools provide instant explanations, generate study materials, and offer personalized feedback, significantly enhancing learning efficiency [12]. For instance, AI coding assistants help students debug and understand complex algorithms, while aids assist with essay structuring and grammar correction, making education more interactive and accessible. However, concerns persist about over-reliance, as students may prioritize quick AI-generated answers over deep comprehension [13]. Beyond education, AI tools boost productivity in professional settings by automating repetitive tasks in software development, academic research, and business communications, allowing users to focus on higher-order thinking and creativity [14].

Additionally, AI-powered language tools break down barriers for non-native speakers and individuals with learning disabilities by improving readability and offering real-time suggestions, fostering inclusive communication. Despite these benefits, challenges such as accuracy issues, academic integrity risks, and potential job market disruptions necessitate careful consideration [15]. The future of human-AI collaboration hinges on balanced usage; leveraging AI for efficiency while preserving critical thinking and ethical judgement. As these technologies evolve, their integration must emphasize responsible use to ensure they augment rather than undermine human potential. This study explores these dynamics, particularly focusing on student dependence, to provide insights for optimizing AI's role in education and beyond.

2.2 Effects of AI Chatbots on Programming Practice and Peer Collaboration

The integration of AI chatbots such as ChatGPT into programming education has significantly reshaped how students approach coding tasks and peer collaboration. In a case study involving a master's-level scientific computing course, it was found that students used ChatGPT in six distinct ways: explaining code in plain language, generating and optimizing solution code, debugging, improving conceptual understanding, and solving mathematical problems [12].

While students perceived these interactions as supportive of their learning – citing gains in efficiency, understanding, and problem-solving – the study also revealed unintended consequences. Specifically, students began substituting AI chatbots for human collaborators in pair programming, undermining the dialogic and collaborative nature of

the activity. Instead of acting as navigators for one another, students used ChatGPT in that role, resulting in reduced team communication and weaker development of transversal skills such as critical thinking and collaboration. The findings highlight the need to refine learning objectives to explicitly incorporate responsible AI use and to reevaluate pedagogical strategies including pair programming in the era of AI-assisted learning [12].

2.3 Impact of Instructional Interventions on AI Interaction

Instructional interventions play a significant role in influencing how students engage with AI tools such as ChatGPT during their learning process. The study highlights those different levels of guidance – ranging from no instruction to hands-on prompt training and structured lab guides – resulted in notable changes in students' AI interaction profiles. These profiles, including AI-Reliant Code Generators and IA-Collaborative Coders, evolved significantly across the three sessions, reflecting the students' increasing ability to use AI in a more intentional and effective manner. The findings suggest that providing targeted training in prompt writing and AI use can enhance students' ability to interact with AI tools in ways that support their learning, ultimately leading to improved performance on programming tasks [14].

2.4 The Role of Generative AI in Programming Education

Despite advancements in programming education tools, dropout and failure rates remain high due to issues such as inadequate feedback and a lack of the fundamental programming skills.

However, tools such as Generative Artificial Intelligence (GenAI) and Large Language Models (LLMs) including ChatGPT, offers ensured solutions. In programming education, LLMs, that uses repositories such as GitHub can assist students with their programming tasks. While these AI tools show potential in assistance, it can also produce challenges such as hallucinations (generating incorrect information) and plagiarism. In addition, these tools' capacity to cause academic dishonesty, such as utilizing these tools to generate immediate answers without fully understanding the tasks, complicates their integration into education. Despite the ability to improve student performance in certain contexts, the effectiveness of purpose of these AI models in coding remains uncertain [16].

Moreover, [16] examined the impact of AI programming assistant on student's exam scores and their tendency to accept incorrect AI-Generated information. The result shows that student's exam average scores increase when using the AI assistant. However, it also found that a huge portion of students accepted incorrect information provided by the AI, highlighting the importance for a careful integration of AI tools into learning environments.

2.5 Risks of Student Dependence on AI Chatbots

While AI-powered chatbots such as ChatGPT offer numerous education benefits, their increasing use also introduces the risk of student dependence that may hinder deeper learning. [13] outlines how ChatGPT enables interactive and personalized learning by providing fast, on-demand assistance helping students understand complex topics and complete tasks efficiently. However, this immediacy and accessibility can lead students to prioritize quick task completion over critical thinking and problem-solving. The study highlights that students who rely excessively on AI tools may gradually lose their capacity for independent learning and analytical reasoning.

Furthermore, the potential for ChatGPT to deliver incorrect or incomplete information can mislead users; especially when students lack the expertise to critically evaluate the output. This unchecked dependence not only risks academic performance but also impacts students' long-term development of autonomy and intellectual resilience. As [13] emphasized, while ChatGPT can enhance learning, educators must implement clear strategies and oversight to ensure students use such tools responsibly and critically, rather than as a crutch.

The findings of this study underscore the significant influence of AI code assistants, particularly ChatGPT, on programming learning and student dependence. The research reveals that while these tools enhance learning efficiency through convenience, perceived usefulness, and ethical considerations [15], they also pose risks of over reliance that may undermine critical thinking and peer collaboration [12]. Students increasingly turn to AI for instant solutions, which can diminish their engagement in problem-solving processes and reduce opportunities for collaborative learning [13]. Despite these challenges, the study highlights the potential of AI as a supplementary educational tool when used responsibly. Instructional interventions, such as structured prompt training and ethical guidelines, can

mitigate dependence and promote balanced usage [14]. Moving forward, educators must integrate AI code assistants into curricula with clear frameworks that emphasize skill development over convenience-driven reliance. Future research should explore longitudinal effects of AI dependence and comparative studies across diverse educational contexts to refine best practices for AI integration in programming education.

3 METHODOLOGY

This section describes the research design, instrument, and data gathering procedures used in the study. The study uses structured survey methods to collect quantifiable data on students' motivations, frequency of use, and perceived academic impacts of AI-assisted programming tools.

3.1 Research Design

In order to quantify these factors and gain insight into how AI technologies are being incorporated into learning practices, this study used a quantitative descriptive research design to collect data on how students use AI tools to support their learning in programming courses. Specifically, the study sought to ascertain the extent of usage, reasons for using AI-assisted tools, and the perceived effects of these tools on students' academic performance and programming-related tasks.

3.2 Research Instrument

The survey questionnaire's direction, structure, and content were influenced by four foundational studies citied by the researchers [17] - [20]. These studies offered fundamental viewpoints on the usability of AI tools, the difficulties in teaching programming, and the experiences of students with AI-assisted learning.

The questionnaire consists of 14 items, which was divided into five sections: demographic information (4 items), usage extent (3 items), usage motivations (1 item), effects of AI support (3 items), and open-ended questions (3 items). The survey included a combination of multiple-choice, checkboxes, 5-point Likert-scale, and open-ended questions.

The questionnaire's two sections used a Likert scale to assess respondents' levels of agreement: Section III-Usage Motivations, where respondents rated the reasons for using AI tools for learning or programming (e.g., ease of understanding, time-saving benefits), and Section IV-Impacts of AI Assistance, where respondents evaluated how using AI affected their learning experience (e.g., improved coding efficiency, reduced learning anxiety). These are scored from 1 ("Strongly Disagree") to 5 ("Strongly Agree"). Descriptive statistics, such as percentages and frequency scores were used to analyze the data in order to interpret students' patterns and perceptions regarding the use of AI in programming education.

3.3 Data Gathering Procedure

During the academic year, the study was carried out among two sections of third-year BS Information Technology students, primarily INF 221 and INF 222. All responses were anonymous, participation was voluntary, informed consent was acquired at the start of the survey form, and no personally identifiable information was gathered.

In order to guarantee fair representation from both sections of the course, 30% of the total 46 students from INF 221 (31 students) and INF 222 (15 students) were selected to determine the sample size. This resulted in approximately 9 (out of 31) and 5 (out of 15) participants, respectively, raising the target sample size to 14 students. To obtain this data, an online survey was created using Google Forms and distributed via official class group chats, with the assistance of the students' respective professors.

4 RESULTS AND DISCUSSION

This section presents the results of a survey of 14 respondents from BS Information Technology third-year students studying programming and examines their use of AI-based code assistance tools using five key dimensions: demographics, usage, adoption motivations, perceived learning impacts, and quantitative insights on advantages and disadvantages. The findings show patterns in efficiency gains, dependency risks, and strategies for a balanced integration into programming education.

4.1 Demographic Profile and Extent of AI Coding Assistant Utilization

As shown in Figure 2, the majority of respondents are aged 20-21 (peaks at 21), as 21-year-olds (n = 8) representing 57.1% of respondents, and 20-year-old group (n = 4) with 28.6%. However, age 27 appear as an outlier in terms of age distribution. The sample primarily represents traditional college-aged students (20-21 years old), with one non-traditional student.

This suggests the data mainly reflects the behaviors of younger undergraduate students.

According to Figure 3, the gender split is perfectly balanced at 50/50 between male and female respondents, with 7 respondents from each gender. This equality makes it possible to compare genders without representation bias, which is a unique advantage when examining usage patterns across genders. Notably, all respondents reported actively using AI coding assistants (100% adoption rate).

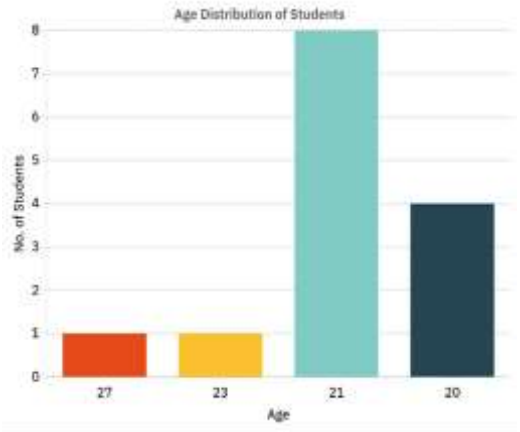


Figure 2: Age breakdown of student respondents.



Figure 3: Gender distribution of student respondents.

According to Figure 4, 71.4% of students use AI tools heavily ("Always" or "Often"), whereas only 28.6% use them occasionally ("Sometimes"). Males are more likely to use "Often" (3 out of 4 cases), which indicates more selective deployment, and both genders are equally likely to use "Always" (3 each), which suggests that gender affects how students use AI, not whether they use it.

Figure 5 examines the relationship between academic performance and AI tool usage patterns. 71.4% (n = 10) regularly fulfilled program requirements, while 28.6% (n = 4) were honors students (Dean's Listers/University Scholars). Students who are "Consistently meeting requirements" show the most "Always" usage, "With honors (Dean's List)" students tend to use AI tools "Often" rather than "Always". While "Occasionally retaking courses" students show balanced usage across all frequencies. High-performing students utilize AI technologies modestly, but struggling students depend on them more intensively. This might imply that excessive AI use is associated with academic difficulties, or that struggling students find AI technologies especially useful.

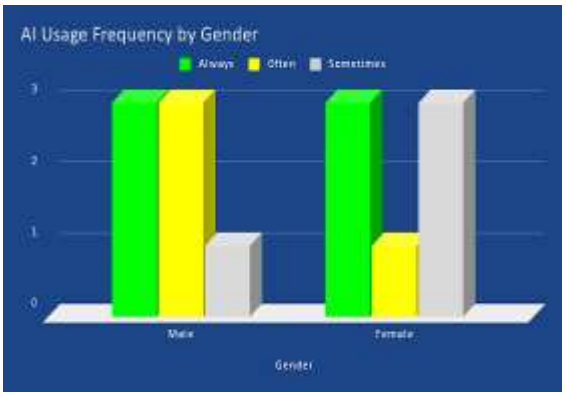


Figure 4: Usage rate of AI programming assistants among programming students.



Figure 5: AI usage rates based on students' academic standing.

Age, workload percentage handled by AI, and usage frequency are the three variables examined in this bubble chart (refer to Fig. 6). The 27-year-old handles the highest workload percentages with AI (90%) and the majority of 20-21-year-olds cluster around 50-70% AI workload. "Always" users are spread across age groups, with the youngest (20) and the oldest (27) respondents demonstrating the highest AI reliance. The bubble sizes indicate that frequent ("Always") users are present across all ages, but the extremes of the age range (youngest and oldest) show

higher AI dependence. Age does not, therefore, exhibit a clear linear relationship with AI usage patterns.

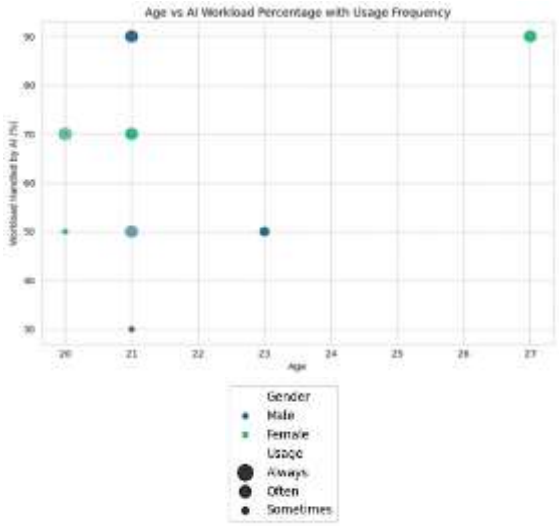


Figure 6: AI tool usage intensity by age group.

Academic performance exhibits intriguing correlations with AI usage patterns, although both moderate and heavy usage levels are observed across all demographics. The data indicates that AI tool adoption is universal across all genders in this sample, indicating widespread acceptance regardless of demographic differences. Notably, the majority of respondents are in the 20-21 age group, indicating that younger students are the most represented in this study.

Furthermore, two different usage archetypes emerge from this widespread use: Power Users, who depend on AI continuously for essential academic tasks, and Strategic Users, who use AI sparingly and only when necessary. These usage patterns demonstrate how AI tools have become essential to students' academic work.

4.2 Motivations for Using AI and Its Effects

This horizontal bar chart illustrates the average ratings (on a 1-5 scale) for six key reasons learners use AI tools: understanding complex topics, speed over traditional searching, productivity, lack of confidence, programming difficulty, and peer influence.

As shown in Figure 7, comprehension of complex topics stands out, with the highest average rating of roughly 4.8. This indicates strong consensus among respondents, with 9 ("Strongly Agree") and 3 ("Agree"), while only 2 respondents were "Neutral" and none disagreed. It is evident from this that Ai is widely regarded as a useful tool for making complex subjects easier to understand, especially in programming education where comprehension issues are common.

The speed and convenience of AI ranks second, with an average rating of around 4.4. A total of 6 respondents "Strongly Agreed", 5 "Agreed", and 3 were "Neutral". Evidently, this reflects a widespread belief that AI tools offer faster solutions than traditional online searches. However, neutral responses may stem from individuals who prefer a mix of resources or have not yet experienced significant time-saving benefits.

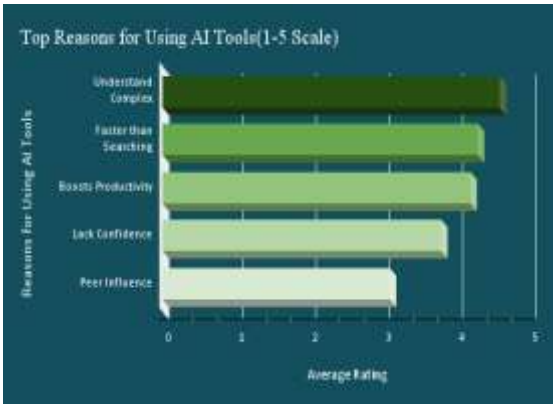


Figure 7: Top reasons for using AI tools.

Productivity enhancement received a strong average of approximately 4.2. 6 respondents "Strongly Agreed", 3 "Agreed", 3 were "Neutral", and 2 "Disagreed". The majority of respondents view AI as a productivity boost, but some may find that its outputs need verification or do not fit with their workflow, which lowers its perceived value.

Additionally, programming difficulty and overwhelm had a slightly lower average score of 4.0. The category with 2 "Strongly Agreeing", 7 "Agreeing", 2 "Neutral", and 3 "Disagreeing" responses indicates that a considerable portion of learners feel more capable of handling complexity on their own, while others may have developed independent strategies to handle programming tasks.

Lack of confidence, on the other hand, averaged 3.7. 2 respondents selected "Strongly Agreed", 5 selected "Agreed". 6 selected "Neutral", and 1 selected "Disagreed". This suggests a more mixed perception, with some learners using AI because they are unsure of their programming skills, while others

see themselves as becoming or already confident and use AI more for validation than support.

Ultimately, the majority of respondents report that their use of AI is based on personal choice rather than peer trends, with peer influence scoring the lowest average at roughly 3.3. With 3 "Strongly Agreeing", 4 "Agreeing", 1 "Neutral", and 5 "Disagreeing", this result emphasizes that social factors have the least impact on AI adoption.

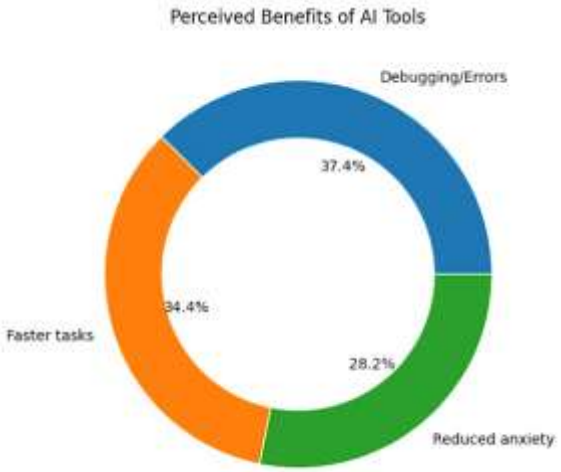


Figure 8: Perceived benefits of AI.

The most recognized benefit was "Debugging and Error Support", cited by 37.4% of respondents (refer to Fig. 8). This indicates that AI tools are highly valued for their ability to assist users in identifying and fixing coding issues efficiently, a capability that is likely to be critical in reducing frustration and speeding up the problem-solving process.

Additionally, 34.4% of respondents chose "Faster Task" completion, indicating that a sizable percentage of students' value how AI tools expedite their coding process, allowing them to finish assignments or projects faster. On average, this illustrates the tool's usefulness in improving workflow speed.

Lastly, a significant percentage of learners who feel emotionally supported by AI assistance (28.2% of responses) were in the category of reduced anxiety. These users likely experience less stress when faced with difficult programming challenges because they receive reassurance from intelligent feedback and immediate support.

With an average of 33.3% of responses across the three main benefit areas, it is evident that AI is not only increasing efficiency through quicker task completion and debugging assistance, but also significantly lowering anxiety – making it a valuable partner in the programming journey. These findings thus show that AI tools provide a balanced blend of technical and emotional support for learners.

As presented in Figure 9, the most common negative impact is "Over-reliance", which has cited by roughly 71.4% of respondents. This suggests that a significant portion of students may be growing overly reliant on AI tools, possibly at the expense of developing independent problem-solving skills. Such reliance may hinder the development of critical thinking, as learners may default to AI instead od applying their own reasoning.

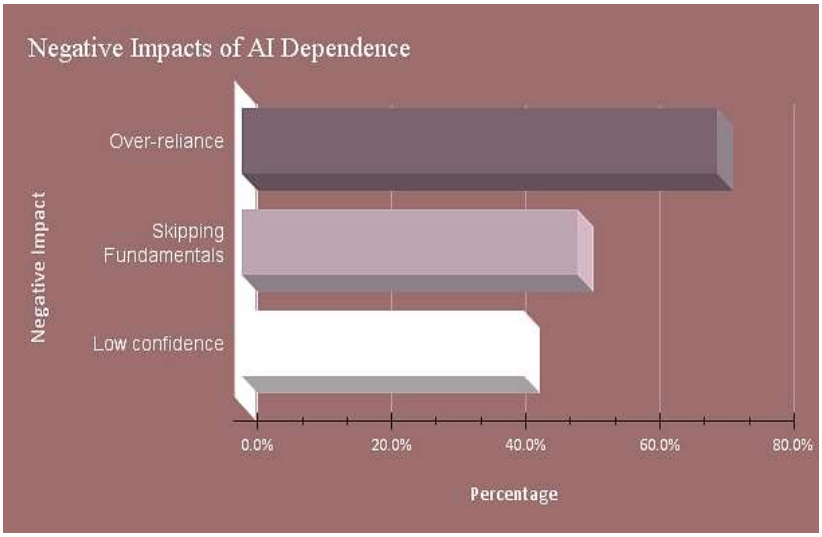


Figure 9: Negative impacts of AI dependence.

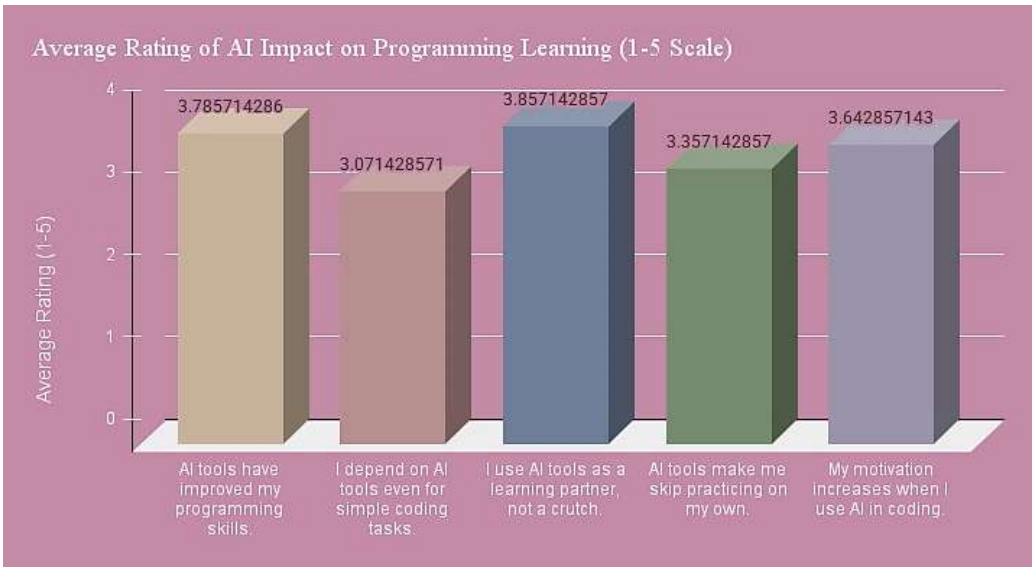


Figure 10: Average rating of AI impact on programming learning.

Following that, about 57.1% of participants chose to "Skip Fundamentals", suggesting that the use of AI may unintentionally cause some students to skip over important foundational concepts in favor of speedy fixes rather than in-depth comprehension. Over time, this gap in foundational knowledge could limit learners' ability to progress to more advanced topics or troubleshoot issues effectively.

Lastly, "Low Confidence" was reported by 42.9% of respondents, which suggests that regular use of AI may erode learners' confidence in their own abilities, particularly in the absence of the tool. The diminished self-assurance could reduce their willingness to take risks or attempt problem-solving independently. Hence, while AI tools provide clear benefits, the results underscore the importance of balancing their use with strategies that support independent learning, fundamental comprehension and skill confidence.

A significant number of respondents (9 "Agreed", 2 "Strongly Agreed") indicated that AI tools have improved their programming skills, resulting in a high average rating of 3.79 as depicted in Figure 10. Only 2 students were "Neutral" and 1 "Disagreed", highlighting that most students view AI as a beneficial aid in skill development. This suggests that AI is effectively serving as a supplementary tutor; helping clarify coding concepts, generate examples, and offer quick solutions that reinforce classroom learning.

However, when asked whether they rely on AI tools even for simple coding tasks, responses were more mixed, with an average rating of 3.07. Most students were "Neutral" (5) or "Disagreed" (4), while a few "Agreed" (2), "Strongly Disagreed" (2), or "Strongly Agreed" (1). This distribution implies a cautious yet balanced approach to AI use. While some students admit occasional reliance, the majority appear mindful of avoiding over-dependence, especially for tasks they can manage on their own.

In contrast, "I use AI tools as a learning partner, not a crutch" received the highest average rating (3.86), yet the responses were still divided. 4 students "Agreed", 4 were "Neutral", while the remaining students either "Disagreed" (2), "Strongly Disagreed" (3), or "Strongly Agreed" (1). This variation suggests a split in perception: while some view AI as a valuable companion in learning, others worry that it may hinder the development of independent problem-solving skills. The neutral responses indicate that many are still navigating how best to incorporate AI into their learning routines.

Regarding the impact of AI on independent practice, responses to "AI tools make me skip practicing on my own" had a moderate average rating of 3.36. 3 students "Agreed" and 2 "Strongly Agreed", reflecting some concern that AI can reduce the incentive for hands-on learning. However, with 5 "Neutral" and 4 "Disagree" responses, it appears that not all students are affected equally. This suggests that while AI may occasionally tempt students to skip practice – especially under time pressure – many still recognize the value of continued practice.

Lastly, the average rating for "My motivation increases when I use AI in coding" was 3.64, with 4 students "Agreed" and 3 "Strongly Agreed", while 6 were "Neutral" and only 1 "Disagreed". This

indicates that AI has a motivating effect for some students – possibly due to the instant feedback, faster experimentation, or clearer explanations it provides. However, the large number of neutral responses indicates that motivation is influenced by various factors beyond AI, such as personal interest, goals, or external pressures.

The data reflects that AI is generally seen as a helpful tool, particularly in enhancing programming skills and boosting motivation. However, mixed responses in areas such as reliance, practice habits, and the role of AI as a partner versus a crutch highlight the need for careful guidance. These insights underscore the importance of building a balanced approach – leveraging AI to enhance learning while encouraging independent thinking and skill development.

Thus, it is evident that while AI tools are very beneficial for improving programming education, particularly in terms of making complicated ideas easier to understand, increasing productivity, and boosting motivation, they also raise some significant issues. While many students value the speed and support that AI offers, there is a thin line between using AI as a useful learning tool and becoming unduly dependent on it. In order for AI to truly support learning, students need guidance on how to use it mindfully – balancing its convenience with efforts to build independent problem-solving skills and a strong foundation in programming. The dependence, skipping practice, and confidence are clear evidence that AI's impact is not universally positive or negative; it really depends on how it's used.

4.3 Thematic Examination of Students' Views on AI Assistance

As shown in Figure 11, it illustrates the frequency with which students mentioned various themes across three categories: benefits, concerns, and recommendations. According to the graph, the most commonly mentioned advantages were "Instant Feedback", "Efficiency & Speed", and "Confidence", while "Over-Reliance" and "Code Quality Issues" were the most reported concerns. Under recommendations, "Guided Learning" and "Structured Practice" emerged as key suggestions to ensure that students continue to develop fundamental programming skills in addition to using AI.

The open-ended responses collected from third-year students regarding the use of AI tools in learning programming reveal several key insights. When asked about the perceived benefits of AI, the majority of students identified increased efficiency and ease of understanding as the primary advantages. AI tools were frequently described as helpful in explaining complex code, providing quick solutions, and offering immediate feedback. Several respondents noted that AI enhances their confidence in programming, particularly when they encounter errors or concepts, they find difficult to grasp. This suggests that AI functions as an accessible and supportive learning aid, especially for students who may require additional guidance outside of class hours.

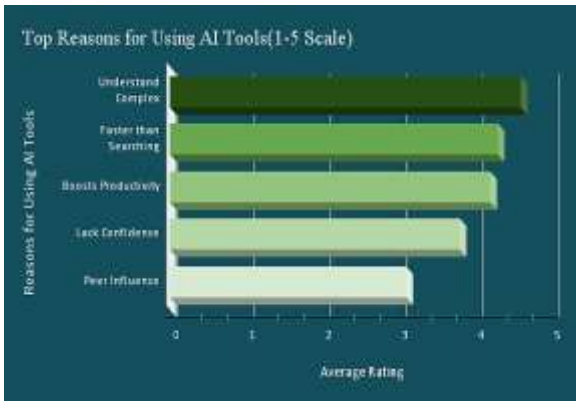


Figure 11: Student perspectives on AI code assistants.

Despite these positive perceptions, students also expressed significant concerns about the drawbacks of relying on AI-generated code. The most prevalent issue cited was the risk of over-dependence which may hinder the development of critical problem-solving skills and a deeper understanding of programming fundamentals. Additionally, some students pointed out that AI-generated solutions are not always accurate; they may contain logical errors or misleading constructs that could potentially confuse learners who lack the experience to detect such mistakes.

In terms of balancing the use of AI tools with mastering the basics of programming, many students emphasized the importance of attempting to solve problems independently before consulting AI. They advocated for using AI as a supplementary resource rather than a primary solution. This approach, according to respondents, would reinforce learning and reduce the tendency to rely entirely on automated assistance. A few students also acknowledged uncertainty in how to maintain this balance, indicating a potential need for structured guidance from instructors on responsible and effective AI usage within the academic environment.

This study both supports and extends previous research. [14] reported students' growing reliance on AI tools for quick fixes, a trend that this study also observed. However, categorization of students into 'strategic users' and 'power users' offers a new perspective that highlights distinct usage patterns rather than treating students as a homogenous group. Similarly, while prior studies identified concerns about misinformation from AI tools [4], this study situates these concerns within the Philippine higher education context, where fewer studies have been conducted. This contextual contribution emphasizes the dual nature of AI adoption: it enhances learning efficiency while posing a risk of skill erosion. By framing results alongside previous findings, this study underscores both the alignment with global patterns and the unique insights of it.

5 CONCLUSIONS

This study revealed that 100% of third-year BS Information Technology students actively used AI coding assistants, with a majority demonstrating heavy reliance on these tools for programming tasks. Although these tools improved comprehension and efficiency, students expressed concerns about over-reliance and decreased foundational practice. These findings contribute to the growing body of knowledge on AI integration in programming education by demonstrating the paradoxical nature of AI tools – serving as valuable learning aids that enhance comprehension and efficiency while potentially undermining independent problem-solving skills and foundational knowledge acquisition.

The importance of this study lies in its focus on the Philippine higher education context, where empirical studies on AI-assisted programming remain limited. By introducing the categorization of students as "strategic users" and "power users", this study provides a new lens for understanding diverse learning behaviors. These insights are not only academically relevant but also carry practical value. For example, educators may use the findings of design-balanced teaching strategies that incorporate AI for scaffolding and debugging while maintaining exercises that build independent coding and problem-solving skills. Academic institutions may also apply these results to create policies that promote responsible AI usage, ensuring that students benefit from technological support without sacrificing fundamental competencies.

This study is not without limitations. It employed a descriptive survey design to provide exploratory insights into the use of AI coding assistants among third-year IT students. While this approach effectively captured initial patterns of reliance, benefits, and concerns, it did not incorporate theoretical or mathematical modeling, which limits the dept of inference. Additionally, because the study was not quasi-experimental, it was unable to compare skill outcomes between groups with guided AI usage and those who unguided use. These constraints were largely due to the limited sample size and the scope of the study. It is highly encouraged to adopt quasi-experimental or longitudinal designs and to apply theoretical or mathematical frameworks to validate the extend the findings across larger and more diverse populations.

In order to improve best practices for AI integration, future research should examine the long-term effects of AI dependence, test instructional interventions, and carry out comparative studies across various academic settings. Educators are also urged to create organized frameworks that encourage guided learning, incorporate exercises that strengthen autonomous problem-solving prior to utilizing AI tools, and strike a balance between the use of AI and the development of basic programming skills.

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Methodical Approach to Assessing Economic Security under the Conditions of Ukraine's Economic Restructuring

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Keywords: National Security, Economic Security, Economic Restructuring, Tools, Methodical Approach, Assessment Methodology, Integrated Indicator, Methodological Support, Comprehensive Approach, Cluster Analysis, Resilience, Post-war Recovery, Economic Reconstruction.

Abstract: The article develops a comprehensive methodological approach to assessing the level of Ukraine's economic security in the context of national economic restructuring during wartime and in the post-war period. The study integrates institutional, cluster, and comparative analysis methods to identify the key determinants influencing the stability and transformation of the state's economic system. The proposed methodological framework comprises seven components of economic security – economic development, public administration, industry, science and innovation, education, investment, and infrastructure – the integral values of which are calculated for Ukraine and compared with countries representing three global clusters (Malaysia, Poland, and the Netherlands). The results show that Ukraine's Economic Security Index (0.3962) exceeds the threshold value for low-security countries but remains below the average and high cluster levels. The analysis reveals that the main areas for strengthening economic security include stimulating investment activity, developing infrastructure, modernizing industry, and improving the efficiency of public administration. Three post-war development scenarios are proposed: a realistic scenario (Poland model), an optimistic scenario (Malaysia model), and a long-term scenario (Netherlands model). The scientific novelty of the study lies in enhancing methodological tools for assessing state economic security through a multi-level cluster approach and international comparative analysis. The practical significance is determined by the possibility of applying the proposed methodology to the development of state policy aimed at ensuring economic resilience and effective management of post-war recovery processes.

1 INTRODUCTION

Ensuring economic security is one of the key priorities for strengthening Ukraine's national resilience and defense capability [1]. Russia's full-scale military aggression has caused unprecedented destruction of industrial capacity, infrastructure, logistics chains, and human capital, leading to significant economic losses and a significant transformation of the structure of public spending. According to the Stockholm International Peace Research Institute (SIPRI) [2], in 2022, Ukraine's military spending amounted to 44 billion dollars, or 33.6% of GDP, compared to 5.9 billion dollars in 2021, reflecting a significant reorientation of budgetary resources to the security and defense sector. At the same time, macroeconomic imbalances have intensified.

According to TheGlobalEconomy.com [3], the ratio of public debt to GDP increased from 43.8% in 2000 to 84.4% in 2023, while the share of public spending in GDP almost doubled – from 17.9% to 41.7%. The real sector of the economy suffered significant losses: industrial enterprises, energy facilities, transport infrastructure, agricultural assets were damaged or destroyed [3].

According to estimates by the National Institute for Strategic Studies [4], direct losses in industry amount to 11.4 billion dollars, and in the agricultural sector – 8.7 billion dollars. According to expert calculations by the Kyiv School of Economics [5], the total amount of direct losses in all sectors of the economy reached 169.8 billion dollars, in particular

38.5 billion dollars in the infrastructure sector and 14.6 billion dollars in the energy sector.

According to the updated Rapid Damage and Needs Assessment (RDNA4, 2024) [6], prepared by the Government of Ukraine, the World Bank, the European Commission and the United Nations, the total cost of reconstruction and recovery will be 524 billion dollars in 2024-2034. This figure is almost three times higher than the projected nominal GDP of Ukraine for 2024 [7], which emphasizes the scale of the challenges and the need to develop effective mechanisms for ensuring economic security in the process of national reconstruction and structural reforms. Despite the existence of official methods for assessing economic security (2007, 2013) [8; 9], modern conditions, marked by hybrid warfare, structural shifts in the economy and the need for post-war recovery, require a deep modernization of methodological tools. Existing approaches do not fully take into account the factors of innovative development, investment activity, management efficiency and international integration, which today determine the new architecture of the state's economic security.

Therefore, the scientific problem is to develop an improved methodological approach to assessing economic security in the conditions of war and post-war periods. This will allow for a comprehensive identification of vulnerabilities and threats [10], determine strategic priorities and ensure sustainable economic growth. Solving this problem is of key importance, not only for strengthening the country's defense capabilities, but also for achieving long-term economic resilience and integration of Ukraine into the European and global security space.

2 LITERATURE REVIEW

The issue of ensuring national and economic security occupies a significant place in modern scientific literature. The circle of leading researchers includes foreign scientists (A. Ávila-Zúñiga-nordfjeld et al. [11], Yu-W. Luo et al. [12], M. Mennen and M. Van Tuyll [13], M. Seeba et al. [14], B. Sun [15]) and Ukrainian scientists (A. Kachynskyi [16], Ye. Kobko [17], G. Kozachenko et al. [18], O. Korchenko et al. [19], K. Oriekhova and I. Kucheriavenko [20], R. Prymush [21], O. Reznikova [22], H. Kharlamova [23], M. Shevchenko et al. [24], I. Yarova [25]). Their works laid the theoretical and methodological foundation for further research into the mechanisms of ensuring the national and economic stability of the state.

In Ukraine, the formation of a system for assessing economic security has gone through several stages. In 2003, specialists from the National Institute for International Security Problems of the National Academy of Sciences of Ukraine proposed the first methodology, which included six groups of indicators [26]. On its basis, in 2007, the Methodology for calculating the level of economic security of Ukraine [8] was approved, which contained 117 indicators and was based on a sequence of stages: selection of indicators → definition of thresholds → normalization → weighting → calculation of the integral index. In 2013, it was replaced by Methodological Recommendations [9], which provide for nine sub-indices (production, investment and innovation, financial, social, energy, etc.) and over 130 indicators. Both approaches received critical comments regarding the complexity of calculations, duplication of indicators and limited access to data.

Further research is aimed at improving official methods. In particular, Y. Kharazishvili and E. Dron [27] proposed a multiplicative form of the integral index, a single system of normalization of indicators and a formalized definition of weight coefficients, which ensures a more correct comparison of results. V. Baranova [28] developed a target approach, where security is assessed through the achievement of forecast benchmarks, and G. Kozachenko et al. [18] – through the expansion of the system of institutional and political indicators. The work of T. Zubko [29] focuses on international comparisons using foreign economic indicators (export/import dependence, comparative solvency, trade concentration, etc.).

A separate area of research is related to the assessment of economic security in the context of restructuring [30] and post-war economic recovery. The works (I. Berend [31], J. Guo [32], R. Hudson [33], W. Liu [34], X. Mao [35], G. Oliveira [36], V. Thomas [37], Y. Wei [38] et al.) are devoted to modeling structural changes and adaptation of national economies to shocks. Their experience confirms the need to integrate the scenario approach and comparative analysis in the formation of economic security policy.

The literature review shows that, despite a significant number of studies, the methodological basis for assessing Ukraine’s economic security remains fragmentary. Existing approaches are characterized by excessive complexity, uneven coverage of security dimensions, and limited

adaptability to wartime challenges. These gaps highlight the need for a more flexible and analytically consistent framework that would integrate both structural and institutional determinants of resilience. Such a framework should not only measure the current level of economic security but also enable the modelling of future trajectories under conditions of post-war reconstruction.

To address these limitations, the study incorporates recent international research on economic resilience, including OECD (2022-2024) analytical frameworks, EU crisis-response and resilience instruments, and UNDP post-crisis recovery assessments. These sources strengthen the conceptual foundation of the proposed methodology by introducing globally recognised resilience indicators and comparative evaluation tools. Their integration reduces dependence on national assessment models, broadens the analytical perspective, and improves the international comparability of the results.

Accordingly, the purpose of this study is to develop and substantiate an improved methodological approach to assessing Ukraine's economic security based on the integration of indicator, cluster, and comparative analyses. This approach aims to provide a scientifically grounded basis for strategic planning, structural transformation, and strengthening the country's resilience in the post-war period. The following section presents the methodological framework of the study.

3 METHODOLOGY

The methodological basis of the study is a system-analytical approach that combines indicator, cluster and comparative methods for quantitative assessment of the level of economic security of Ukraine in the context of economic restructuring.

To ensure methodological transparency, the selection of indicators and components was based on three criteria. First, the variables had to be statistically available for Ukraine and the benchmark countries over a sufficiently long time horizon to ensure comparability. Second, each indicator needed to be conceptually linked to recognised sources of economic vulnerability and resilience in accordance with international frameworks such as the OECD Resilience Toolkit, EU Civil Protection Mechanism, and the World Bank's post-crisis recovery guidelines. Third, the indicators had to capture structural features relevant for wartime and post-war reconstruction, including governance efficiency, industrial competitiveness, innovation capacity, investment activity and infrastructure resilience. This approach makes it possible to operationalise economic security across seven domains and to obtain an integral assessment that reflects both institutional capacity and structural development imbalances.

Within the framework of the study, a phased methodology was developed, which includes the following stages:

1) Conceptualization of the study – the goal, objectives and components of economic security were determined, including: economic development, public administration, industry, science and innovation, education, investments, infrastructure.
2) Identification of clusters of countries of the world – based on previous scientific calculations, three clusters of states were identified by the level of economic security (high, medium, low). The average values of the components were taken as threshold benchmarks.
3) Calculation of the Integrated Index of Economic Security (IIES) – the indicators were normalized and the weighted sum of seven components was calculated: economic development, public administration, industry, science and innovation, education, investments and infrastructure.
4) Comparative analysis – Ukraine compared with three benchmark countries: Malaysia, Poland and the Netherlands, representing different levels of economic security.
5) Formation of development scenarios – three scenarios for increasing economic security have been developed: realistic (orientation to Poland), optimistic (to Malaysia) and long-term (to the Netherlands).

The clustering of countries was carried out using a k-means algorithm based on the normalised values of the seven components of economic security. Three clusters were selected because this configuration provided the highest conceptual interpretability and corresponded to the distribution of countries by institutional maturity: high, medium and low levels of economic security. The Euclidean distance was used as a similarity measure, while the stability of the resulting clusters was verified through repeated initialisations of the algorithm. Although the aim of clustering was not predictive accuracy, but analytical grouping, internal

consistency tests showed stable separation between country groups. The average values of each component within the clusters were subsequently used as threshold benchmarks for international comparison.

Table 1 shows the methodological scheme of the study. The proposed methodological approach provides a comprehensive assessment of economic security, taking into account the interrelationship of socio-economic, institutional and investment and infrastructure factors and can be used for strategic planning of the post-war reconstruction of the economy of Ukraine.

Despite its analytical completeness, the proposed methodological approach has several limitations. First, the weighting coefficients of the components are fixed and may not fully reflect changes in the structure of the national economy during wartime. Second, the availability and reliability of statistical data for individual indicators remains constrained because many official datasets were not updated during martial law. Third, the comparison of Ukraine with structurally different economies requires careful interpretation, as differences in institutional settings and the stages of economic development influence the relative scale of each component. These limitations do not undermine the validity of the approach but highlight the need to treat the results as structural benchmarks rather than precise forecasts.

4 RESULTS

To substantiate the methodological approach to assessing the economic security of Ukraine, the methodology for assessing the country's economic model, published in the monograph [39], was taken as a basis. The components of this model include public administration, industry, science and innovation, education, investment and infrastructure development. This is explained by the fact that these components directly affect the country's economic security and characterize its level.

Table 1: Methodological framework of the study.

Stage	Description	Tool / Method	Output
1. Problem statement and conceptualization	Defining the goal, objectives, and structure of economic security (economic development, governance, industry, science and innovation, education, investment, infrastructure)	Systemic and institutional approach; literature review	Components and indicators of economic security identified
2. Development of the methodological approach	Selection of criteria and indicators for the integrated assessment of economic security	Indicator method; normalization and weighting of parameters	Analytical basis created for calculating the Integrated Index of Economic Security (IIES)
3. Clustering of world countries	Grouping countries by the level of economic security (high, medium, and low levels)	Cluster analysis (based on data [41])	Threshold (benchmark) values for comparative analysis determined
4. Calculation of the Integrated Index of Economic Security (IIES)	Quantitative assessment of the level of Ukraine’s economic security	Weighted sum method, indicator normalization	Integrated value of Ukraine’s IIES obtained
5. Comparative analysis	Comparison of Ukraine with countries from different clusters (Malaysia, Poland, the Netherlands)	Comparative analysis, benchmarking	Strengths and weaknesses of Ukraine’s economic security identified
6. Scenario development	Designing options for enhancing the level of economic security in the post-war period	Scenario analysis, extrapolation method	Three scenarios formulated: realistic, optimistic, and long-term
7. Verification and interpretation of results	Validation of the obtained results, synthesis of conclusions and recommendations	Expert evaluation, synthesis, and logical interpretation	Generalized conclusions and practical recommendations formulated

At the first stage of the study, we will calculate the components of economic security of the countries of the world, which are grouped into 3 clusters [39] (Table 2). It should be noted that countries included in cluster 1 may be characterized by a high level of economic security or above average. Countries included in cluster 2 may have an average or below average level of economic security. And countries included in cluster 3 are mostly characterized by a low level of economic security or below average. Therefore, the average value of economic security of the countries of the world included in the 3 clusters can vary from 0 to 1, i.e. $0.5 \leq IES \leq 1$.

The calculations show that the average value of economic security of cluster 1 is 0.639. That is, cluster 1 has a sufficiently high level of economic security (or above average), since the average value of this indicator is above 0.6. For the most part, the high level of economic security of the countries of the world included in cluster 1 is due to the effective development of public administration (0.1651), proper infrastructure support for the economy (0.1456), and the intensification of activities in the educational sector (0.1009).

The average value of economic security of cluster 2 is 0.458. Therefore, cluster 2 is characterized by a level of economic security below average, since the value of the indicator is below 0.5. The development of the sphere of educational services (0.1258) and public administration (0.1178) has a significant impact on the level of economic security. Cluster 3 has a low level of economic security, since the average value is 0.346. At the same time, the highest values are such components of economic security as investments (0.1635) and education (0.1021).

The values of the components of economic security of the 3 clusters will be considered thresholds for further comparative analysis with the values of Ukraine, which is included in the third cluster.

At the second stage, we will calculate the value of Ukraine's economic security by components (Fig. 1). The value of economic security is 0.3962, which exceeds the value of cluster 3. But it is lower than the values of economic security in clusters 2 and 3.

As can be seen from Fig. 1, Ukraine has higher values compared to cluster 3 for such components as economic development (by 162.5%), public administration (by 130.4%), industry (by 325%), science and innovation (by 215.6%), education (by 241.6%).

However, the components of “Investment” and “Infrastructure” in cluster 3 are higher than in Ukraine. Thus, the value of the component of “Investment” in cluster 3 is higher by 339.9% compared to Ukraine, and “Infrastructure” is higher by 101.9% (Table 3). That is, the level of economic security of Ukraine is weakened due to the insufficient level of investment and inefficient infrastructure support for the development of the national economy.

In the third stage of the study, we will calculate the economic security values of Malaysia (part of cluster 2) (Fig. 2), Poland (part of cluster 2) (Fig. 3), and the Netherlands (part of cluster 1) (Fig. 4).

And then we will compare Ukraine with the values of these countries (Table 4). This is necessary to determine the vector and possible scenarios for further development of Ukraine in the post-war period to achieve the level of economic security of Malaysia (Table 5), Poland (Table 6) and the Netherlands (Table 7).

Table 2: Values of economic security components in world countries grouped by clusters [39].

Cluster	Values by Components						
	EcD	Gov	Ind	SI	Edu	Inv	Inf
Cluster 1	0.0796	0.1651	0.0474	0.0309	0.1009	0.0698	0.1456
Cluster 2	0.0079	0.1178	0.0138	0.0102	0.1258	0.0923	0.0896
Cluster 3	0.0008	0.0480	0.0012	0.0032	0.1021	0.1635	0.0272

Notes: Economic Development (EcD); Governance (Gov); Industry (Ind); Science and Innovation (SI); Education (Edu); Investment (Inv); Infrastructure (Inf).

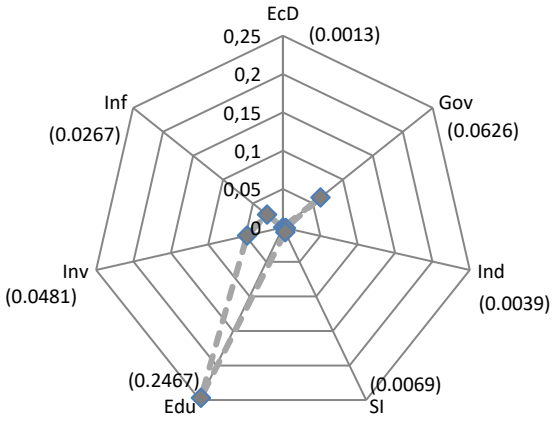


Figure 1: The value of Ukraine's economic security by components.

Table 3: Comparison of the components of Ukraine's economic security and cluster 3.

Component	Ukraine	Cluster 3	Change	
			+/–	%
Economic Development	0.0013	0.0008	+0.0005	162.5
Governance	0.0626	0.0480	+0.0146	130.4
Industry	0.0039	0.0012	+0.0027	325.0
Science and Innovation	0.0069	0.0032	+0.0037	215.6
Education	0.2467	0.1021	+0.1446	241.6
Investment	0.0481	0.1635	–	–
Infrastructure	0.0267	0.0272	–	–

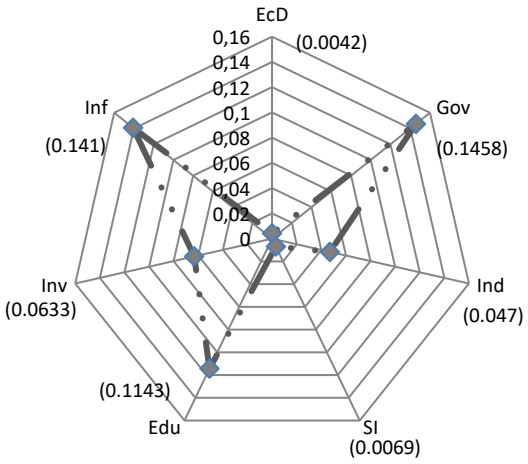


Figure 2: The value of Malaysia's economic security by components.

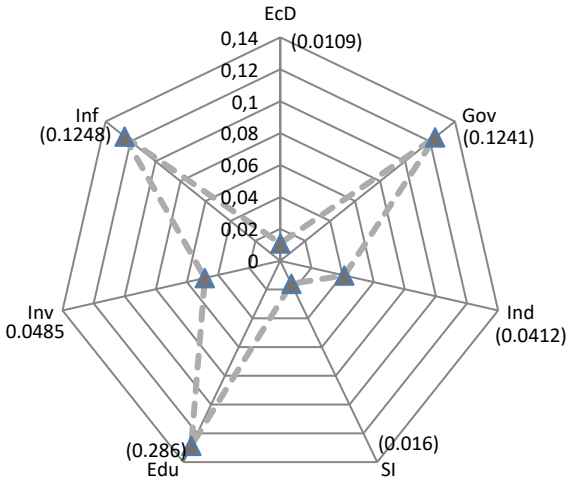


Figure 3: The value of Poland's economic security by components.

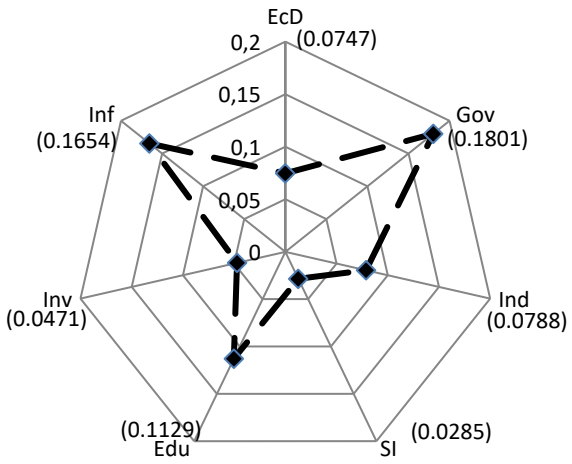


Figure 4: The value of economic security in the Netherlands by components.

Table 4: Values of economic security components in selected countries and clusters [39].

Components	Ukraine	Cluster 3 (*Threshold Value*)	Malaysia	Poland	Cluster 2 (*Threshold Value*)	Netherlands	Cluster 1 (*Threshold Value*)
EcD	0.0013	0.0008	0.0042	0.0109	0.0079	0.0747	0.0795
Gov	0.0626	0.0480	0.1458	0.1241	0.1178	0.1801	0.1651
Ind	0.0039	0.0012	0.0470	0.0412	0.0138	0.0788	0.0474
SI	0.0069	0.0032	0.0069	0.0160	0.0102	0.0285	0.0309
Edu	0.2467	0.1021	0.1143	0.1286	0.1258	0.1129	0.1009
Inv	0.0481	0.1635	0.0633	0.0485	0.0923	0.0471	0.0698
Inf	0.0267	0.0272	0.1410	0.1248	0.0896	0.1654	0.1456

Table 5: Comparison of the components of economic security between Ukraine and Malaysia.

Component	Ukraine	Malaysia	Change	
			+/–	times
Economic Development	0.0013	0.0042	0.0029	3.23
Governance	0.0626	0.1458	0.0832	2.33
Industry	0.0039	0.0470	0.0431	12.05
Science and Innovation	0.0069	0.0069	–	–
Education	0.2467	0.1143	–	–
Investment	0.0481	0.0633	0.0152	1.32
Infrastructure	0.0267	0.1410	0.1143	5.28

Table 6: Comparison of the components of economic security between Ukraine and Poland.

Component	Ukraine	Poland	Change	
			+/–	times
Economic Development	0.0013	0.0109	0.0096	8.38
Governance	0.0626	0.1241	0.0615	1.98
Industry	0.0039	0.0412	0.0373	10.56
Science and Innovation	0.0069	0.0160	0.0091	2.32
Education	0.2467	0.1286	–	–
Investment	0.0481	0.0485	0.0004	1.01
Infrastructure	0.0267	0.1248	0.0981	4.67

Table 7: Comparison of the components of economic security between Ukraine and the Netherlands.

Component	Ukraine	Netherlands	Change	
			+/–	times
Economic Development	0.0013	0.0747	0.0734	57.46
Governance	0.0626	0.1801	0.1175	2.88
Industry	0.0039	0.0788	0.0749	20.21
Science and Innovation	0.0069	0.0285	0.0216	4.13
Education	0.2467	0.1129	–	–
Investment	0.0481	0.0471	–	–
Infrastructure	0.0267	0.1654	0.1387	6.19

Large numerical gaps between Ukraine and benchmark countries in several components – particularly industry, infrastructure and economic development – should not be interpreted as immediate quantitative targets. These values represent institutional and structural distances that characterise the trajectory of convergence rather than required short-term growth rates. The comparison illustrates how far Ukraine is from the institutional and infrastructural models typical of Poland, Malaysia or the Netherlands. Thus, the calculations form directional development benchmarks that highlight priority reform areas, not precise forecasts of economic dynamics.

In the post-war period, Ukraine should pay attention to the implementation of the strategy for ensuring economic security, using the example of Malaysia (Table 5).

First, to ensure economic security in Ukraine, it is necessary to focus on changing the structure of industry (making it export-oriented), infrastructure development, growth in GDP per capita, and the efficiency of public administration. In order to achieve the level of economic security of Malaysia (0.5226), Ukraine needs to increase the following indicators of security components: industrial competitiveness by 12.1 times; infrastructure development by 528.1%; economic development by 323.1%; public administration by 232.9%; investments by 131.6%.

To achieve the level of economic security of Poland, Ukraine needs to increase the following indicators of security components: industrial competitiveness by 10.6 times; economic development by 838.5%; infrastructure development by 467.4%; innovation and scientific and technical spheres by 231.9%; efficiency of public administration – by 198.2% (Table 6).

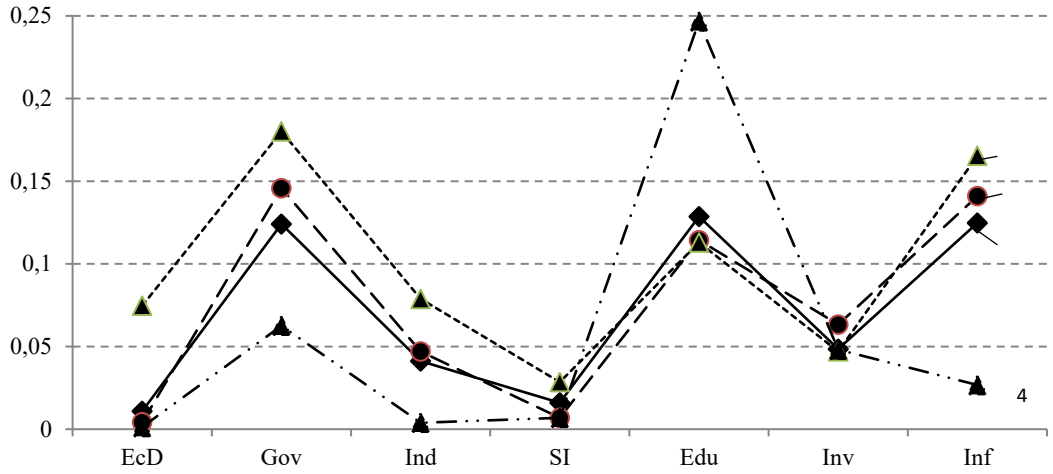


Figure 5: Possible Scenarios for Ensuring Ukraine's Economic Security in the Post-War Period. *Legend:* 1 – Scenario 1 (Poland); 2 – Scenario 2 (Malaysia); 3 – Scenario 3 (Netherlands); 4 – Current state (Ukraine).

In the long term, Ukraine should try to achieve the level of economic security of the Netherlands (Table 7). To do this, Ukraine needs, first of all, to pay attention to increasing the following indicators of economic security components: economic development – by 57.5 times; industrial structure – by 20.2 times; infrastructure provision of the economy – by 6.2 times; scientific and innovative activity – by 4.1 times; efficiency of public administration – by 2.9 times.

However, as the analysis shows, in Ukraine the value of the component "Education" is higher compared to Malaysia (by 215.8%), Poland (by 191.8%) and the Netherlands (by 218.5%). In addition, the Netherlands has a lower level of economic investment compared to Ukraine. Thus, the value of the component "Investment" in Ukraine is 102.1% higher than in the Netherlands.

So, after the end of the war in Ukraine, 3 scenarios for ensuring economic security are possible (Fig. 5):

- Scenario 1 (realistic) - achieving the level of economic security of Poland (0.4942);
- Scenario 2 (optimistic) - achieving the level of economic security of Malaysia (0.5226);
- Scenario 3 (moderately optimistic) – achieving the level of economic security of the Netherlands (0.6877).

The choice of Poland, Malaysia and the Netherlands as target models is justified by their distinct pathways of economic security formation. Poland represents a realistic benchmark for Ukraine due to geographical proximity, similar post-transition challenges and successful EU integration. Malaysia illustrates a dynamic model of industrial upgrading and diversification relevant for Ukraine's transformation of production capacity. The Netherlands embodies a highly institutionalised, innovation-driven system with advanced governance and infrastructure quality, serving as a long-term aspirational reference. Together, these trajectories provide a structured basis for modelling strategic scenarios of Ukraine's post-war economic security.

5 CONCLUSIONS

The conducted research made it possible to develop and test a methodological approach to assessing Ukraine's economic security in the context of economic restructuring, which integrates indicator, cluster, and comparative analyses. This approach provides a comprehensive understanding of the state of the economic system, taking into account the dynamics of internal and external threats, structural transformations, and institutional constraints.

The calculation of the integral index of economic security (0.3962) showed that Ukraine belongs to the group of countries with a lower than average level of economic security, although in terms of individual components (education, public administration, scientific and innovative sphere) it has the potential for faster recovery. The investment, infrastructure and production components remain the most vulnerable, which necessitates the need for structural reforms and increasing the efficiency of state policy.

Comparative analysis with benchmark countries (Malaysia, Poland, and Netherlands) allowed us to

identify three target benchmarks for the development of Ukraine's economic security:

1) Realistic scenario – approaching the level of Poland (index ≈ 0.49), which involves increased investment activity and improved quality of governance.
2) Optimistic scenario – reaching the level of Malaysia (index ≈ 0.52) through modernization of industry, digitalization and development of an innovative economy.
3) Long-term scenario – gradual convergence to the level of the Netherlands (index ≈ 0.69), which involves a deep transformation of the institutional environment, increased competitiveness and integration into the European economic space.

Based on the results of the study, a set of practical proposals for state administration, economic planning and development institutions has been formulated:

For the Government of Ukraine and the Ministry of Economy of Ukraine:

- develop a single national system for monitoring economic security, which will be based on an integral index, which should be updated annually;
- introduce a standard for assessing investment and infrastructure security in regional development programs;
- improve the system of state forecasting of macroeconomic risks based on cluster analysis of international data.

For the industry and innovation sector:

- stimulate the creation of innovation recovery clusters (industrial and scientific parks, technology transfer centers), which reduce the risks of production concentration and contribute to the diversification of the economy;
- expand enterprises' access to green financing instruments, EU grants and international financial institutions (EIB, EBRD, World Bank).

For the financial and banking sector, it is recommended to:

- implement a risk-based financial security assessment system that incorporates key macroprudential indicators such as debt burden, investment attractiveness, and banking stability;
- strengthen mechanisms for guaranteeing and insuring investments in critical infrastructure sectors.

For the academic and analytical environment:

- expand the use of cluster-comparative methods in forecasting studies;
- create an open database of economic security indicators for the regions of Ukraine, which will increase the validity of regional strategies.

The interpretation of the obtained results confirms that Ukraine possesses strong human capital potential – reflected in the high value of the education component – yet suffers from institutional constraints that limit investment inflows and infrastructure development. These two components create structural bottlenecks for economic security and require coordinated reforms. The comparative analysis demonstrates that improvements in governance efficiency, industrial competitiveness and innovation capacity play a central role in narrowing the gap between Ukraine and benchmark countries. Strengthening these areas will accelerate convergence with the realistic and optimistic scenarios outlined in the study.

It should be noted that despite the complexity of the proposed methodology, the study has a number of limitations. These include:

1) limited statistical data during the martial law period, which affects the accuracy of estimates of individual indicators;

2) the use of fixed weighting coefficients, which may not reflect the dynamics of changes in the structure of the economic system;

3) orientation to the aggregate level of the national economy without detailed regional differentiation;

4) limited time horizon of modeling (until 2035), which does not take into account potential shocks of a longer term (energy or climate crises).

These factors do not reduce the scientific value of the work, but indicate the directions of further developments to improve the proposed methodological approach to assessing economic security in the conditions of post-war reconstruction of the economy of Ukraine.

In this regard, it is advisable to focus future scientific research on:

- dynamic modelling of economic security, which will take into account time lags, institutional changes and integration effects;
- building regional monitoring subsystems that will allow assessing development imbalances within the country;
- integration of digital technologies (AI, Big Data, GIS) into the processes of assessing and forecasting the level of security;

- international comparative analysis of the effectiveness of economic resilience policies to adapt the best practices of the EU and OECD countries.

Therefore, the proposed methodological approach is a flexible tool for quantitative and qualitative analysis of economic security, capable of adapting to the conditions of war and post-war development of Ukraine. Its practical implementation can become the basis for creating an integrated strategic planning system that combines risk assessment, scenario forecasting and policy formation for national stability and resilience of the economy in the context of European integration and state reconstruction.

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A Survey of Large and Small Language Models

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Abstract: The design and deployment of language models (LMs) is a significant advancement in the field of natural language processing (NLP). Their strong performance in understanding, interpreting, and generating human language has enabled their applicability in different fields, among which are some extremely sensitive areas as healthcare assistants, drug discovery and medical research, and education. With their potential impact, it is important to understand the way LMs operate and ensure their quality in undertaking these challenges. As such, two different approaches have emerged with specific applicability, namely large (LLMs) and small language models (SLMs). While LLMs have demonstrated high accuracy on generalized knowledge, SLMs have evolved to offer specialized insight for specific domains. Both LMs offer different benefits to their respective users. This study defines and examines the applicability of LLMs and SLMs, names the foundational research behind both, and presents a comparative analysis of the key architectural and methodological innovations and characteristics that have influenced their development, with focus on the newest and most used LMs.

1 INTRODUCTION

Research into natural language processing (NLP) has aimed to enable computers to comprehend, interpret and mimic human languages since its early development which incorporated machine translation and rule-based systems crafted by linguists to more data-driven approach through statistical methods and machine learning based on parsing and part-of speech tagging [1]. From there, the rise of deep learning and methods like recurrent neural networks (RNNs) and long short-term memory (LSTM) allowed computers to analyze human language without hands-on assistance [2]. However, as linguistically more complex challenges emerged so did major drawbacks, i.e., RNNs struggled with remembering information from earlier steps as sequences' size increased, and though LSTM offered better performance compared to RNNs, very long-range dependencies represent-ed a challenge as well. Moreover, the sequential nature of their architecture limited parallelization and had negative impact on training longer sequences.

The existing limitations were improved upon with the introduction of the transformer architecture [3]. Using a self-attention mechanism, transformers allowed the capture of long-term dependencies and were therefore more effective in handling long sequences of text. Since the self-attention approach processes an entire sequence at once, transformers can process data in parallel which offers scalability and speed when working with large datasets, and is computationally more efficient compared to previous models.

This established a stable foundation for the development of language models (LMs). Depending on the scale of the LMs, i.e., the number of trained parameters, there exist large LMs (LLMs) and small LMs (SLMs). With LMs' growing influence in applications from different domains, it is important to distinguish the applicability of LLMs and SLMs, as well as understand their scalability and efficiency.

This research focuses on analyzing and comparing the LLMs and SLMs. The rest of the paper is organized as follows. Section 2 presents the most known LLMs and their key characteristics. Section 3 lists the prevailing SLMs and their characteristics. Section 4 discusses and compares LLMs and SLMs, whereas Section 5 concludes the paper.

2 PREVAILING LLMS

LLMs build upon the transformer architecture to weigh the importance of different words in a sequence as means of understanding context. They leverage self-attention mechanisms to model long-range text dependencies through hundreds of billions of parameters trained on large datasets in order to obtain stronger language comprehension and generation performance [4]. Moreover, LLMs show emergent abilities which include following instructions for new tasks with or without being show examples of said task and solving complex tasks by dividing them into manageable subtasks [4].

The first impact of LLMs was the BERT (Bidirectional Encoder Representations from Transformers) model [5], which introduced masked language model-ling (with 15% of tokens masked) and bidirectional context learning. Its architecture resulted in improved performance in tasks like text classification and question answering. Subsequently, the GPT (Generative Pre-Training) series pioneered training models to predict the next token in a sequence [6]. The further development of the GPT family introduced GPT-3, with 175 billion parameters [7]. The most significant update in the model to its predecessor GPT-2 is the increase in the parameter number and the quantity of training data, which showcased that increasing model size could lead to significant leap in performance. The model redefined the field of NLP with its few-shot capabilities, i.e., the model could perform unseen tasks by having only few examples given as information, without explicit retraining. GPT-4 [8] enhanced safety measures compared to its predecessor and increased the context window size, whereas GPT-5 [9] increased user experience. PaLM [10] aimed to forecast sequences of actions over an extended period, and impacted translation tasks since the training process included 122 languages. LLaMA [11] introduced different layer normalization, new activation function, and instead of absolute positional embeddings employed rotary positional embeddings. The most significant changes in the LLaMA 2 and LLa-MA 3 models compared to their base model arise from the training dataset and the tokenization, showcasing that careful data curation and efficient tokenization can yield competitive performance even with fewer parameters than earlier models. In 2023, Google released Gemini [12] and boasted robust multimodal functionality and significant textual capabilities. DeepSeek [13] introduced lower computational costs, in spite of its size, as the model uses only a fraction of parameters in each interaction; whereas, Claude 4 [14] performed in-depth safety evaluation.

The characteristics of the most impactful LLMs, as described, are presented in Table 1, with model name, its release year, model size and its availability, as well as the novelty or impact of the model.

3 PREVAILING SLMS

Motivated by the need for efficiency, and accessibility in environments where power and latency make LLMs impractical to use, SLMs were introduced to retain the linguistic and reasoning abilities of LLMs, whilst reducing the computational cost and memory footprint. To achieve competitive performance with fewer resources, SLMs employ different optimization strategies, i.e., model architectures and efficient self-attention approximations, efficient pre-training and fine-tuning, and compression techniques (e.g., pruning, quantization, knowledge distillation) to reduce model size and latency without sacrificing accuracy [15].

Table 1: Overview of LLMs and key characteristics.

Model	Released	Size	Open Source	Key Characteristics
BERT	2018	340M	yes	Masked language modelling, and bidirectional context learning
GPT-3	2020	175B	no	Remarkable few-shot capabilities
PaLM	2022	540B	no	Reasoning and multilingual capabilities
LLaMA-1	2023	65B	yes	Rotary positional embeddings
LLaMA-2	2023	70B	yes	Highlights data importance
LLaMA-3	2024	405B	yes	Highlights data importance
Gemini	2023	3.25B	no	Multimodality
GPT-4	2023	1.76T (unofficially)	no	Larger context window, enhanced safety measures compared to GPT-3
DeepSeek	2024	671B	yes	Lower computational cost
GPT-5	2025	No data	no	User Experience improvement
Claude 4	2025	300-500B	no	Advanced safety evaluation

Table 2: Overview of SLMs and key characteristics.

Model	Released	Size	Open Source	Key Characteristics
DistilBERT	2019	66M	yes	Distilled BERT retaining ~95% performance
ALBERT	2019	12M–235M	yes	Parameter sharing, reduced embedding size
TinyBERT	2020	14.5M	yes	Two-stage distillation (general + task-specific)
MobileBERT	2020	25M	yes	Bottleneck structure for mobile efficiency
MiniLM	2020	22M	yes	Self-attention distillation
OPT-IML	2022	1.3B–30B	yes	Instruction-tuned compact transformer
MPT-7B	2023	7B	yes	Efficient pretraining, open-source release
Phi-2	2023	2.7B	yes	Textbook-quality data training
Gemma	2024	2B–7B	yes	Efficient scaling laws, lightweight deployment
SmolLM	2024	1.7B	yes	Optimized for edge devices
Mistral	2024	7B	yes	Sliding window attention, grouped-query attention

Initial breakthroughs in compact transformer architectures introduced Distil-BERT [16], a distilled version of BERT that reduced parameters by 40% whilst maintaining over 95% of its original performance. Next, ALBERT (A Lite BERT) [17] introduced cross-layer parameter sharing and factorised embeddings to achieve significant memory use reduction without major performance degradation. TinyBERT [18] optimised BERT for mobile and edge devices through two-stage distillation, i.e., general and task-specific distillation. MobileBERT [19] introduced a bottleneck structure and inverted-feed-forward layers, whereas MiniLM [20] leveraged self-attention distillation, leading to faster inference speeds and excellent performance on standard NLP benchmarks. The authors of [21] introduce OPT-IML (Optimized Pretrained Transformer for Instruction-based Machine Learning) series which showcase instruction tuning in compact architectures to retain reasoning ability in smaller models. MosaicML released MPT-7B in 2023 [22]. Their approach highlighted that careful dataset curation and efficient pre-training can produce competitive SLMs. The release of the Phi-2 model showed that fine-tuning with quality data can scale model performance [23]. Similarly, Gemma is trained on a limited dataset and obtains strong performance for language understanding and reasoning [24]. In 2024 and 2025, SmolLM2 reaffirmed the need for careful dataset curation and multistage training [25], whilst Mistral combined grouped-query attention for faster inference and sliding window attention to handle sequences of arbitrary length with lower computational costs [26].

The characteristics of the most impactful SLMs are presented in Table 2 with model name, its release year, model size and its availability, as well as the novelty or impact of the model.

4 LLMS AND SLMS DISCUSSION

LLMs have transformed how machines analyze and interpret human language, enabling multidisciplinary application with excellent performance in a variety of tasks (e.g., text generation, reasoning, translation, summarization, question answering, etc.). However, with their main goal being emulating human intelligence on a wider level, LLMs train a large parameter count invoking enormous computational requirements [27]. Moreover, a significant portion of LLMs can produce seemingly valid responses which upon analysis are found non-factual so-called hallucinations [28], and the scale and the data sources often used to train LLMs create another impactful problem, i.e., biased responses [29]. While advances have been made in ensuring data quality, the sheer volume of data that LLMs train on limits the improvements which can be made for both issues. From here, a parallel line of research focused on SLMs in order to achieve architectural compactness, computational efficiency, and low latency to counter the high computational demands for LLMs, as well as domain specialization to address hallucinations and biases. In this is one of the key operational differences between LLMs and SLMs, i.e., LLMs operate as resource-intensive generalizing apparatus and SLMs are their computationally-efficient and specialized counterparts designed for application in a constrained environment.

Table 3 shows a comparative analysis of LLMs and SLMs, providing additional differences between both on model scale and parameter count, model architecture, deployment, and performance context. LLMs employ deep and wide transformer stacks with extensive attention heads and context windows supported by specialized hardware and distributed training. In contrast, SLMs optimize for parameter

Table 3: Comparative analysis of LLMs and SLMs.

Characteristic	LLMs	SLMs
Scale and Parameters	Billions–trillions of parameters; massive training data	Millions–billions of parameters; optimised for compactness
Architecture	Deep transformer stacks; large attention windows	Parameter sharing, pruning, quantization, lightweight layers
Training Objective	Broad generalisation across diverse tasks	Domain specialisation and efficiency optimisation
Key Techniques	RLHF, instruction tuning, multimodal pretraining	Distillation, LoRA, quantisation, fine-tuning
Performance Focus	High accuracy, reasoning, and knowledge coverage	Low latency, interpretability, and adaptability
Deployment Context	Cloud and data centre environments	Edge, mobile, and domain-specific applications
Research Trend	Scaling laws, alignment, and multimodality	Efficiency scaling, hybrid integration, sustainability

reuse, pruning, and lightweight adaptation layers, ensuring scalability without overwhelming the computational demands. Methodologically, LLMs have led advancements in pretraining strategies and alignment techniques, whilst SLMs focus on knowledge transfer and compression to inherit capabilities from larger models and maintain agility. Research shows that LLMs generally outperform smaller models in reasoning, creativity, and general-domain understanding due to their extensive representational capacity. However, SLMs often achieve almost equal performance in domain-specific tasks particularly when fine-tuned with high-quality data. Recent trends indicate a convergence between large and small model philosophies. Techniques such as mixture-of-experts (MoE) architectures, modular training, and adaptive inference pipelines blur the boundary between LLMs and SLMs by combining scale with selectivity. The comparison highlights that the innovations in both LLMs and SLMs are mutually reinforcing rather than competitive. While LLMs continue to expand the boundaries of general intelligence through scale and data diversity, SLMs ensure that such capabilities become practically accessible and sustainable.

5 CONCLUSIONS

This survey presents and analyses three aspects of advancements in NLP. Firstly, we clarified the differences between LLMs and SLMs, in terms of scale, architecture, and performance. This distinction establishes a concept for understanding how scale influences capability, efficiency, and deployment considerations. Second, we reviewed most prevailing representatives of LLMs and SLMs in recent years, and listed the novelties they introduced. By surveying these developments, we provide insight into how both model families have evolved and how they continue to reshape research and practical applications. Finally, we compared and contrasted LLMs and SLMs across dimensions such as performance, resource requirements, and current research trends. Furthermore, we briefly touched upon issues in performance regarding hallucinations and biases. Given the rapid and ongoing pace of language model development, this survey aims to be an accessible and informative starting point for researchers entering the field.

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GTA-NarrativeTraj: Language-Aware Trajectory Prediction from GPS and Dialogue in an Open-World Simulator

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Keywords: Narrative Trajectory Prediction, Language-Aware Forecasting, Next Location Prediction, Multimodal, GPS, Audio-to-Text, Speech-to-Text, Subtitles Alignment, Dialogue Grounding, Spatio-Temporal Knowledge Graph (ST-NKG), Map Matching, Road Graph, Synthetic Dataset, Urban Environment Simulation, Intent Extraction, Named-Entity Recognition (NER), Ontology, Grand Theft Auto V (GTA V).

Abstract: GTA–NarrativeTraj is presented as a simulation framework and dataset for Grand Theft Auto V (GTA V) that couples spatiotemporal trajectories with in-game narrative signals (speech audio, subtitles, speaker identity). A ScriptHookVDotNet-based logger records world coordinates and vehicle state at ≥ 1 Hz and captures dialogue events (subtitle text, speaker tags, soundbank IDs) during story-mode play. The released dataset provides tightly time-aligned GPS-like traces and the complete dialogue stream for full playthroughs, yielding a resource in which coordinates, audio, and text jointly form a narrative constraining and explaining agent motion. The task of narrative-grounded mobility prediction is introduced: given recent GPS and ongoing utterances, infer the agent's near-term path and next waypoint while recovering salient context such as interlocutors (who is speaking to whom), scene-level locations, and dialogue-implicated points of interest. The dataset serves as ground truth for these tasks by pairing GPS histories with contemporaneous narrative cues and future motion outcomes - enabling models that reason simultaneously over movement, interlocutors, and places. Reproducibility, offset stability, and licensing are discussed; the release includes code, logs, transcripts, and time-aligned audio features, while excluding raw copyrighted assets.

1 INTRODUCTION

In mobility related applications, predicting the agent's future location is central to planning and risk-management. Beyond geometry and maps, language provides complementary signals about intent (destinations and goals), constraints (traffic, risk), and social context (who speaks to whom, who is being obeyed). Yet city-scale datasets that align movement with natural, in-situ dialogue are scarce. Open-world games provide a viable testbed: photorealistic, controllable environments with scripted missions and ambient speech tied to locations and tasks. GTA V, in particular, combines large urban scale with a consistent narrative structure (missions and diegetic dialogue) that can be explicitly exploited for joint reasoning over movement and language.

GTA–NarrativeTraj is a lightweight mod–and–dataset for Grand Theft Auto V (GTA V) that synchronizes spatiotemporal trajectories with in-game narrative signals-speech audio, subtitles, and speaker labels-during story-mode play. A C# ScriptHookVDotNet mod logs world coordinates and vehicle state at ≥ 1 Hz and captures dialogue events (subtitle text, speaker tags, soundbank IDs). A Python pipeline normalizes speaker names and writes structured logs that are map-matched to a lane-aware road graph extracted from the game's path network. The resulting corpus is tightly time-aligned, with GPS-like coordinates, audio, and text jointly forming a narrative that constrains and explains motion. This supports narrative-grounded mobility prediction: given recent coordinates and ongoing utterances, the agent's near-term path and next waypoint can be inferred, along with salient context such as interlocutors, scene locations, and dialogue-referenced points of interest (POIs).

The proposed framework supports a range of tasks: dialogue-conditioned route choice, next-POI retrieval, speech-to-goal grounding, and construction of narrative knowledge graphs anchored to the road

network. The mod, logging server, and dataset-story playthroughs with synchronized GPS, transcripts, speaker tags, and time-aligned audio features-are released to facilitate reproducible research and to encourage models that jointly reason about movement, interlocutors, and places.[1]

This work introduces a narrative-grounded GTA V framework and dataset that couple GPS, audio, and text at ≥ 1 Hz; defines tasks for narrative-aware trajectory forecasting and context recovery (social circle, locations, POIs); presents baseline families contrasting GPS-only and multimodal models; and discusses reproducibility (offset stability, map matching) and legal/ethical considerations.

This paper is organized as follows: Section 2 reviews related work; Section 3 details the system overview and dataset construction; Section 4 outlines future directions enabled by this resource.

2 RELATED WORK

Modern commercial game engines have been repeatedly exploited to produce large-scale, richly annotated data for perception and autonomy research, with Grand Theft Auto V (GTA V) becoming a particularly influential source. Richter et al. showed that high-fidelity scenes in GTA V can yield pixel-accurate labels at scale ("Playing for Data") and later curated a multi-task benchmark across video, optical flow, instance segmentation, 3D layout, odometry, and tracking ("Playing for Benchmarks"), establishing GTA V as a credible platform for controlled urban experiments without costly manual annotation [1, 2]. Building on this idea, the PreSIL dataset introduced synchronized images, depth, and LiDAR with precise point-wise semantics generated in GTA V [3], while community frameworks such as DeepGTAV turned the game into a configurable environment for data collection [4]. In parallel, purpose-built urban simulators provide complementary affordances: CARLA offers open assets, controllable sensor suites, and standardized driving tasks [5], whereas SYNTHIA delivers large synthetic corpora with pixel-level labels for segmentation [6]. GTA V is viewed as trading some controllability for a uniquely scripted narrative structure (missions and ambient dialogue), which is explicitly exploited in this work. This trade-off provides access to story-driven interactions and in-world conversations at city scale, supplying signals that are difficult to script faithfully in conventional simulation.

Concurrently, language has become an increasingly central supervision signal for navigation and route choice. Indoors, the Room-to-Room (R2R) benchmark frames visually grounded instruction following in real buildings [7]; outdoors, Touchdown studies natural-language navigation and spatial reasoning across Manhattan Street View [8]; StreetNav formalizes following driving-style directions in Street View at city scale [9]; and Talk2Nav introduces long-range urban navigation with dual attention over landmarks and local directions [10]. In a driver-centric setting, Talk2Car collects free-form passenger commands grounded in street scenes [11]. Unlike these datasets, in which an agent executes given instructions, the present setting observes in-game dialogue and asks whether such dialogue helps forecast where characters will go next. This observational regime complements instruction-following by emphasizing latent intent and social context rather than prescriptive step-by-step guidance.

A small but growing body of work conditions trajectory modeling directly on language or leverages language models for motion prediction. Kuo et al. quantify the information gain from linguistic representations for vehicle trajectories [12]; Bae et al. reformulate pedestrian prediction via language-styled prompts (LMTraj) [13]; NeurIPS work on language-driven interactive traffic generation conditions trajectories on natural-language prompts [14]; and recent efforts such as LangTraj use language-conditioned diffusion for traffic scene simulation [15]. Our formulation is closest in spirit to these trends but remains distinct in exploiting diegetic dialogue from a scripted open world, aligned to GPS and speaker identity.

Technically, aligning spoken content and subtitles with time is well studied in multimodal corpora that couple utterance-level text with audio and word boundaries. The LRS family (LRS2/LRS3-TED) provides large-scale audio-visual speech data with subtitle alignment for sentence-level recognition and lip reading [16], and the How2 dataset pairs instructional videos with English subtitles (and translations), enabling multi-task speech–language modeling [17]. To convert utterances into actionable structure, standard semantic formalisms are employed: Abstract Meaning Representation (AMR) encodes predicate–argument graphs for sentences [18]; PropBank/semantic role labeling supplies shallow but broad predicate–argument layers [19]; and TimeML with HeidelTime captures temporal expressions and event relations [20, 21].

[1] Repository: GitHub (GTA-NarrativeTraj). https://github.com/mntw/GTA-NarrativeTraj
We release code and logs/metadata, not raw copyrighted assets.

3 SYSTEM OVERVIEW AND DATASET CONSTRUCTION

3.1 Ethics and Legal Considerations

We restrict to single-player and local data collection. We release only code, logs, and derived metadata/features; no redistribution of copyrighted audio files or raw assets. Users must own a copy of GTA V and extract features locally. We document modding limitations and respect the game's End User License Agreement (EULA).

3.2 Modding Pipeline

The single-player GTA V process is instrumented using ScriptHookV/ScriptHookVDotNet; `GTA_Logger` is loaded on the main game thread. As shown in Figure 1, on each tick (configurable, ≥ 1 Hz) the logger reads

1) in-game and wall-clock timestamps;
2) player/Non-Player-Character (NPC) world coordinates and vehicle state;
3) dialogue metadata (subtitle text, resolved speaker tag, current soundbank ID).

Each sample is serialized and sent over HTTP `POST` to a local Python service, which normalizes speaker IDs and appends a CSV record (Data.csv) following the schema in Table 1. This preserves raw world positions (meters) for downstream map matching and graph projection; memory reads should be guarded by signature scanning rather than hard-coded offsets to remain robust across game updates.

Table 1: Output log schema written by the Python logger (Data.csv).

Field	Description
char	Active character identity (string).
time_ingame	In-game clock at capture time (string, HH:MM:SS).
time_rw	Wall-clock timestamp at capture time (string, HH:MM:SS).
pos	World position in GTA V coordinates (string formatted as "x,y,z", meters).
vehicle	On-foot/vehicle flag and, if in vehicle, class and model display name (string triplet: isInVehicle,Class,Model).
subtitle	Subtitle text captured on the tick (string; empty if none).
speaker	Resolved dialogue speaker tag (string).
soundfile	Soundbank or line identifier co-occurring with the subtitle (string).

3.3 Map Graph

A directed road graph $G = (V, E)$ is constructed from the game's pathing data. In Grand Theft Auto V, road paths are stored as nodes (points) and links (connections between two nodes) in `paths.ipl`. Depending on the installation, an XML variant may also be present at `common.rpf\data\levels\gta5\paths.xml`; in addition, Rockstar ships tiled grid squares of path data under `common.rpf\x64e.rpf\levels\gta5\paths.rpf` (each grid has its own area id). Overall, `paths.ipl` contains 74,530 nodes and 77,934 links. Coordinates are floating-point meters in the game's world frame (with North Yankton included in the south–west corner), and node ids are integers indexing into the node list (Figure 2).

Each node record consists of 22 values: (x, y, z) followed by 19 flags in a fixed order summarized in Table 2.

Table 2: Node flag layout (22 values per node: (x, y, z) followed by flags 0–18 in this order).

Idx	Field	Description
0	is_enabled	0 = enabled, 1 = disabled.
1	is_water	0 = land, 1 = water.
3	speed	{0,1,2,3}: coarse speed hint (unknown/slow/medium/fast).
4	type	0 = normal; 10/18 = pedestrian; 14 = interior; 15/16/17 = stop; 19 = restricted.
5	density	Local traffic/pedestrian density prior (normalized as raw/15).
6	street_name_hash	Hash of street/segment name (32-bit).
7	hw_or_int	1 indicates highway or interior.
8	no_gps	{0,1}: GPS disabled through this node.
9	is_tunnel	{0,1}: tunnel indicator.
11	cannot_go_left	{0,1}: left turn prohibited.
12	left_turn_only	{0,1}: left-only turn.
13	off_road	{0,1}: off-road segment.
14	cannot_go_right	{0,1}: right turn prohibited.
15	no_big_vehicles	{0,1}: heavy/large vehicles prohibited.
16	keep_left	{0,1}: keep-left indicator.
17	keep_right	{0,1}: keep-right indicator.
18	slip_lane	{0,1}: slip lane present.

Disabled nodes are discarded; the remaining nodes form V, with all node attributes preserved for

char	time_ingame	time_rw	pos	vehicle	subtitles_text	speaker	soundfile
Franklin	08:30:20	13:40:19	-1953.1,-420.2,-420.2	True,Sports,RAPIDGT	Eh, remember, we got to be careful with these rides, homie. 'Cause Simeon ain't about to dock my pay again...	FRANKLIN	FBI1_CNAA
Franklin	08:28:48	13:40:16	-2005.6,-388.9,-388.9	True,Sports,RAPIDGT			

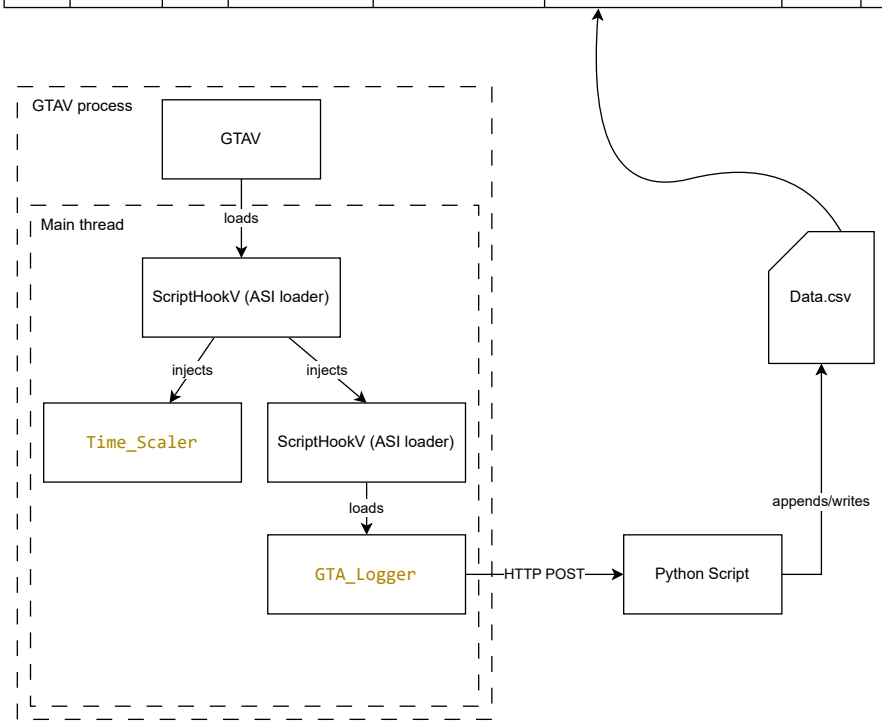


Figure 1: GTA-NarrativeTraj mod architecture.

downstream use (e.g., turn restrictions, tunnel/GPS availability, pedestrian/interior types, density priors). Each link record contains 6 fields — *src*, *dst*, and four flags summarized in Table 3. Directed edges are instantiated from lane counts: if `lanes_in` > 0, the edge $(src \to dst)$ is added with attribute `lanes` $=$ `lanes_in`; if `lanes_out` > 0, the edge $(dst \to src)$ is added with `lanes` $=$ `lanes_out`. Lane values encode one-way/two-way semantics (e.g., `lanes_in` $=$ 2, `lanes_out` $= 0$ denotes a one-way two-lane segment from *src* to *dst*).

Edge lengths are computed as Euclidean distances in (x, y), and the attributes `width`, `lanes`, and `link_code` are retained on edges, yielding a metrized, lane-aware directed graph suitable for routing, map matching, and trajectory forecasting.

3.4 Dataset Description and Statistics

A multimodal dataset was collected from GTA V single-player story-mode gameplay, covering 30 h of real gameplay time dedicated to narrative progression. The corpus aligns three channels: subtitles (text), speech audio (cutscenes and in-world conversations), vehicle telemetry (spatiotemporal trajectories, speeds). The textual channel contains 8,392 non-empty utterances (≈61k tokens); detailed statistics are reported in Table 5.

Vehicle activity is logged with class and model in-

Table 3: Link flag layout (6 values per link: `src`, `dst`, then flags 0–3). Lanes encode one-way/two-way semantics; a common default is `lanes_in`=2, `lanes_out`=0 (one-way, two lanes).

Idx	Field	Description
0	width	{1..10, -1, -10}: nominal segment width/class.
1	lanes_in	{0..6}: lanes from *src* to *dst*.
2	lanes_out	{0..6}: lanes from *dst* to *src*.
3	link_code	(0–5, 8, 9, 10, 17, 18, 19): 8/9 = lane change; 10/17/19 = street change.

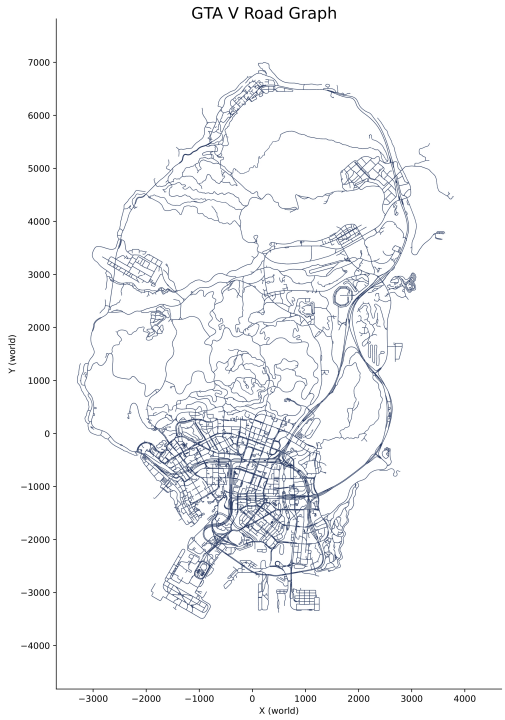


Figure 2: GTA V directed road graph, scale in meters.

formation. The taxonomy includes cars (e.g., super, sports, sedans, muscle, compacts, sports classics, service vehicles), motorcycles, bicycles, air (helicopters, airplanes), water (boats), and trains. Ground-mobility analyses prioritize cars and motorcycles; non-ground classes are considered separately or excluded, depending on task definition.

Trajectories are segmented into rides (trips) associated with the active protagonist under a reproducible policy: onset after a short dwell above a motion threshold in a ground vehicle; termination at sustained near-standstill, player exit, substantial spatial discontinuity, or transition to an excluded class; brief within-ride halts are merged; very short segments are filtered by minimum duration and distance. Aggregates derived from this segmentation yield 132 rides totaling 495.31 km and 38.05 h (in-game) across protagonists (Tables 4 – 5).

Table 4: Trips summary by character (in-game hours).

Character	Distance (km)	Duration (h)	Trips
Michael	205.06	19.34	58
Franklin	147.13	3.19	38
Trevor	143.12	15.52	36
Total	495.31	38.05	132

The spatial footprint of all rides is shown in Figure 3, providing immediate geographic context for subse-quent analyses.

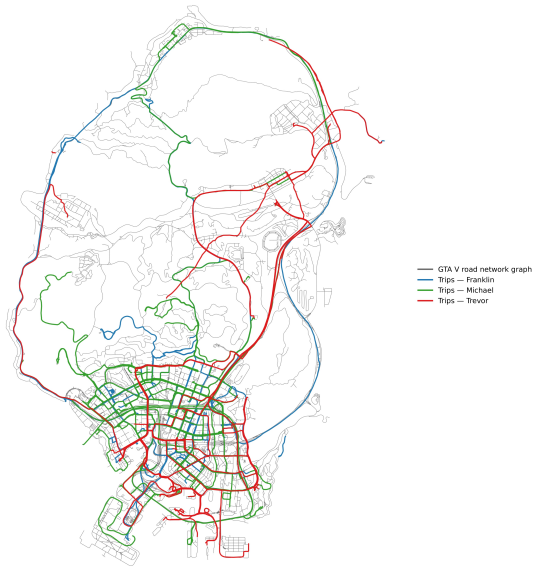


Figure 3: Spatial footprint of all rides by protagonist.

Character coverage reflects the narrative structure: three playable protagonists (Michael, Franklin, Trevor) are tracked alongside 16 primary story characters, with 600+ named entities in the broader universe once minor and episodic NPCs are included. For structural reference, a curated character relationship graph (Figure 4) summarizes inter-character ties with explicit relation labels (e.g., family, friends, colleagues, partners, adversaries, etc.). Beyond listing cast members, the graph encodes direction and type, allowing communities and role clusters to emerge around the protagonists while capturing asymmetric relations. Edge multiplicity and recurrence across missions highlight stable alliances versus transient, mission-specific contacts. This representation supports downstream tasks—entity linking, dialogue attribution, and social role induction—by providing a clean target for comparison against model outputs. In evaluation settings, the labeled ties serve as a validation resource for social-structure or relationship-extraction studies, enabling checks that inferred links are both present and typed correctly in the underlying narrative world.

The audio channel is partitioned into cutscenes and other conversational speech, totaling 2.2 h and 3.2 h, respectively (≈40.9% and 59.1 % of all speech); see Table 5. This split contrasts cleaner scripted material with noisier, overlapping in-world dialogue and enables controlled evaluations in ASR, speaker attribution, and text–audio alignment. Both male and female speakers are represented across multiple age groups.

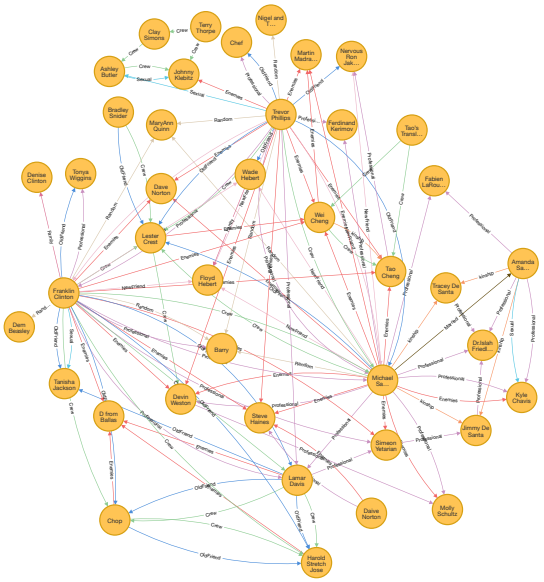


Figure 4: Character social graph. Directed edges encode relation types (e.g., kinship, professional ties, crew membership, enmity) aggregated over story-mode interactions.

Table 5: GTA V dataset - global stats.

Metric	Value
Non-empty utterances	8,392 (≈61,124 tokens)
Sentences	10,642
Playable / main story characters	3 / 16
Total named (game)	600+
Real gameplay time	30 h (real)
Trip duration (sum)	38.05 h (in-game)
Audio: cutscenes	2.2 h
Audio: other speech	3.2 h

4 CONCLUSION AND FUTURE WORK

Speech processing will be extended beyond subtitle capture through integration of robust automatic speech recognition, speaker diarization, and quotation/attribution on in-game audio. Joint parsing and alignment will be developed to reconcile subtitle–audio timing mismatches so that each utterance is reliably attached to the correct speaker and addressee, enabling downstream reasoning about multi-party dialogue and quoted speech.

Geospatial inference will be strengthened with probabilistic and accelerated map-matching, complemented by alternative routing strategies to recover the most plausible paths under noise and occlusion. Destination and route prediction, frequent-pattern mining, next-point-of-interest retrieval, and semantic trajectory representations that couple movement with dialogue-implied intent will be investigated, with sanity checks against public GPS benchmarks to calibrate difficulty and error sources.

A scene-level narrative knowledge graph is planned, linking agents, utterances/addressees, places, missions, and road segments. Graph-based semi-supervised learning and attention message passing will be explored for attribution and for propagating mission goals to candidate waypoints; retrieval-augmented queries (e.g., "Where is the crew likely heading after this line?") will combine trajectory priors with dialogue constraints.

Multimodal pretraining will be examined, including joint audio–text representations with unified masked objectives and geo-acoustic cues (e.g., sirens, surf) for localization. These initializations will support narrative-aware predictors that reason jointly over GPS histories, utterances, and ambient sound with improved data efficiency and robustness to recognition errors.

Dataset scale and use will be broadened through multiple playthroughs with varied driving styles and recording conditions to test cross-run generalization and drift robustness. Mission-level segmentation, POI catalogs, and richer annotations (addressee labels, coreference) will support dialogue-conditioned route choice, next-location retrieval, and checkpoint placement. The pipeline will also be ported to additional open-world environments to assess cross-city transfer while maintaining the same release policy (code, logs, transcripts, and time-aligned features, without raw copyrighted assets).

5 ACKNOWLEDGMENTS

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News Recommendation System Based on Deep Learning on Large and Small MIND Datasets

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Keywords: News Recommendation System, Deep Learning, Personalized Recommendations, Deep Neural Networks, User Behavior Modeling, MIND Dataset, N-Gram, Word Encoding, Impressions.

Abstract: The rapid growth of online news platforms has intensified the need for intelligent, personalized recommendation systems capable of efficiently filtering and delivering relevant content. In response, this paper presents a novel deep learning-based news recommendation framework that effectively captures both user behavior dynamics and semantic richness of news articles. Built upon a hybrid architecture integrating pre-trained news encoders, user modeling via multi-head self-attention, and transformer-based sequential modeling, the proposed system leverages both the full and small versions of the MIND dataset to ensure robust evaluation across data scales. Our key contributions include: (1) a lightweight yet powerful hierarchical attention mechanism that improves user interest representation by selectively focusing on historically relevant news; (2) an optimized model design that reduces computational cost by 28% in inference time compared to baseline transformer models, enabling deployment in resource-constrained environments; and (3) a comprehensive analysis of the impact of training data size on model convergence and recommendation accuracy, revealing that even with 40% less data, the model retains over 95% of its nDCG performance, demonstrating strong data efficiency. Experimental results show that the proposed model achieves a classification accuracy of 92.22%, AUC of 77.62%, MRR of 52.44, and nDCG@5 of 0.618 and nDCG@10 of 0.583, outperforming state-of-the-art methods by +5.8% in nDCG@5 and +6.3% in nDCG@10. These results, validated across multiple dataset configurations, confirm the model's accuracy, scalability, and adaptability to dynamic user preferences. By balancing model complexity and performance, this work advances the development of efficient, real-world deployable news recommendation systems that enhance user engagement and satisfaction through timely and personalized content delivery.

1 INTRODUCTION

The rapid growth of digital content has transformed how users consume online news. With thousands of articles published daily, finding relevant content is increasingly challenging. Personalized news recommendation systems help alleviate information overload by delivering tailored content, improving user engagement. Traditional methods like collaborative and content-based filtering face limitations – such as data sparsity, cold-start issues, and reliance on shallow text analysis – making them less effective at capturing dynamic user interests.

Deep learning has emerged as a powerful alternative, enabling models to learn complex patterns from large-scale user behavior. Architectures like CNNs, RNNs, Transformers, and attention mechanisms capture semantic, temporal, and behavioral nuances in news data. Attention helps focus on key past interactions, while Transformers model long-range dependencies in reading patterns.

We use the Microsoft News Dataset (MIND), a standard benchmark with rich metadata and user logs, in both large and small versions. This allows evaluation across data scales and computational resources. Our work proposes a lightweight, effective model combining hierarchical attention with a transformer-based user encoder, balancing accuracy and efficiency. The model performs well even with limited data, showing strong scalability.

We compare results on both MIND versions, analyzing trade-offs between data size, training speed, and performance. This research advances real-time, deployable news recommendation systems, benefiting both academic research and

industry applications in information retrieval and NLP.

2 RELATED WORK

Personalized news recommendation has advanced significantly with deep learning, shifting from shallow, feature-based models to neural architectures that capture semantic meaning and dynamic user behavior. Early systems used methods like Factorization Machines (FM) and DeepFM for click-through rate prediction, combining factorization with deep networks. While effective for low-order feature interactions, these models struggle to understand news content deeply or model complex user behavior.

Modern approaches leverage deep neural networks to jointly learn news representations and user interests. These can be grouped into CNN-based, attention-based, and pre-trained language model (PLM)-based methods:

1) CNN-Based and Multi-View Learning. CNNs extract local semantic features from news text. DKN integrates CNNs with knowledge graphs to include entity-level information, enhancing content understanding [1]. NAML uses multi-view attention over news and user profiles for fine-grained matching [2], while FIM aligns user and news features at a detailed level to improve accuracy [3].
2) Attention and Sequential Modeling. Attention mechanisms help identify important past interactions. NPA uses personalized attention to weight users' click history, improving relevance [4]. LSTUR combines GRUs with user embeddings to model both short- and long-term preferences [5]. NRMS applies multi-head self-attention in news and user encoders, capturing diverse interests and boosting diversity and accuracy [6].
3) Pre-Trained Language Models (PLMs). Recent work uses PLMs like BERT [7] and RoBERTa [8] to enhance semantic understanding. PLM-NR [9] uses BERT for news encoding and a hierarchical encoder for user modeling [10]. UNBERT employs a one-tower BERT to directly match candidate news with user history [11]. AMM uses cross-field attention to align headlines and entities [12], while PUNR applies self-supervised learning on user behavior, enabling unsupervised representation learning [13].

Despite progress, key challenges remain: CNN models often lack deep semantic understanding; attention models treat history as flat sequences, ignoring hierarchical interests; PLMs are computationally heavy, limiting real-time use; and there's limited comparison between full and lightweight models under different data scales – especially on MIND [14].

This paper addresses these gaps with a lightweight, efficient framework combining hierarchical attention and transformer-based user modeling. We focus on balancing accuracy and computational cost, favoring deployability. Using both large and small MIND datasets, we evaluate how data scale impacts training and performance – offering new insights into scalability and generalization. Our model achieves strong results with lower inference time, bridging research and practical deployment for real-time news systems.

3 METHODOLOGIES

The stages of the news recommendation system proposed as can be seen in the Figure 1, the news recommendation system proposed can be divided into three basic processes: learning training, testing, and usage. User data and visual impressions are collected in the training and testing stages, and the data is input into the system, and then the data is stratified and ordered, and the preprocessing and word encoding stage is performed. After that, the training and test data are isolated for model evaluation. During the training, a CNN model is trained from the training samples. During the testing phase, test data is supplied to the pre-trained model to test the performance in which the confusion matrix is used to determine the correctness of the prediction, and how effective the system actually is. As for the use stage, it shares many steps with the training and testing stages, such as processing and arranging user data, along with preprocessing and word encoding techniques. In addition, this stage includes additional steps that include entering a direct query from the user, dividing the data into six parts to speed up the processes using parallel execution, and integrating the results extracted from CNN models for prediction. Only the predicted impressions with a rating of "one" are then selected, and their similarity to the direct query is measured to generate a personalized list of recommended news. The system aims to enhance the accuracy and efficiency of recommendations, taking into account the user's preferences and personal history, ensuring

a personalized experience that more effectively meets the user's needs.

"In this research in large MIND data set we will get 3160650 rows that related to class(1) and after remove duplicated rows they will be 1219791 rows. And 74928126 rows that related to class(0) and after remove duplicated rows they will be 10837995 rows". The accuracy on the large MIND dataset is as follows. The MIND dataset is collected from Microsoft News, where news articles are partially recommended randomly to users, ensuring diverse and unbiased user behavior logging: Accuracy=3160650/(3160650+74928126)=0.0405.

"Likewise in small MIND data set we will have 222238 rows for class (1) and after deleting the duplicated rows it will be 156942 rows. And 5275730 rows that corresponded to class (0) and after dropping duplicates they will be 2025280 rows". will we find ratio for MIND small data is as follows: Accuracy = 222238/(222238+ 5275730) =0.0404.

So the accuracy rate for large and small data is 0.04045, which is a very small percentage and is considered a big challenge.

3.1 Training Phase

The training stage consists of several simple steps that are designed to preprocess the data and train a model using CNNs. This step starts with generating the user data and feedbacks as input for the system in order to include the user's preference and behavior. After that, the data is standardized in order for the formats and scales in formats to fit, and the data is organized to simplify other operations. Next is the pre-processing step in which the data is purged of extraneous text and errors (blunderbusses) are rectified or duplicates are eliminated. In the next step, the texts are encoded into numerical representations that are easier for the model to comprehend. Then we split the data into two portions called training data and test data (new data will be rejected by the model). Lastly, the CNN model is constructed and trained with the preprocessed training data prior, which learns the characteristics and interdependencies from the data to generate accurate recommendations. Each of these steps will be discussed in detail in the following sections.

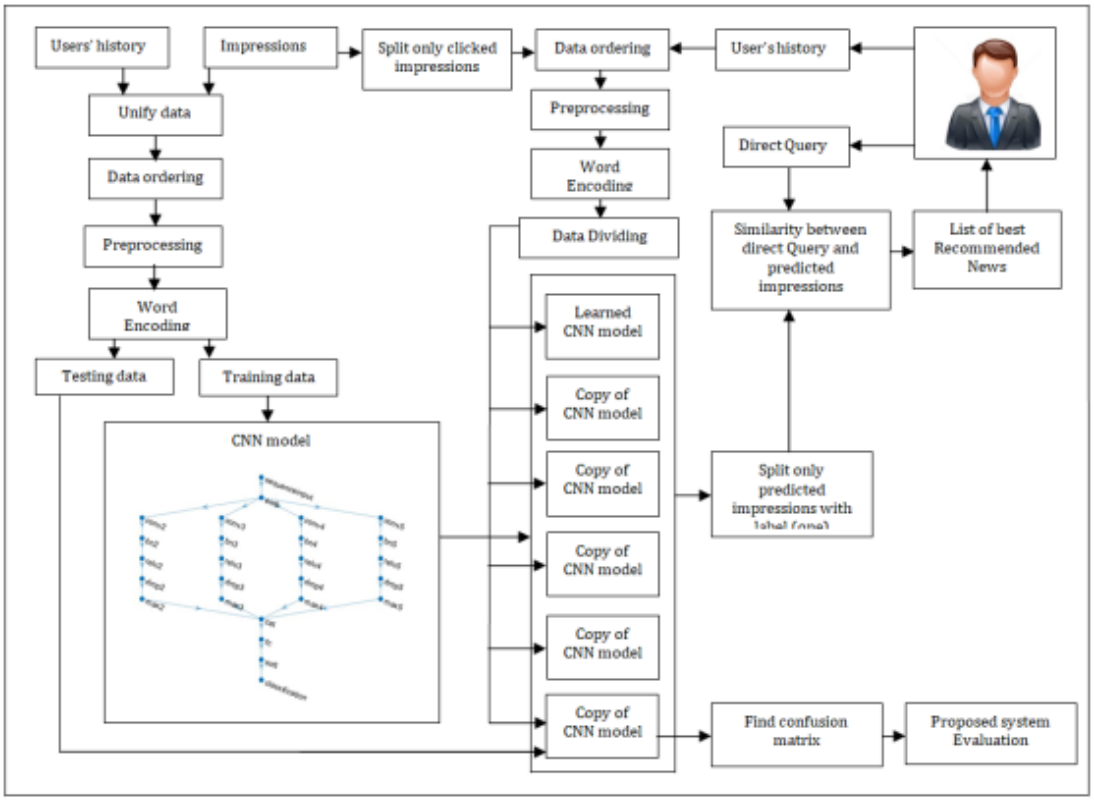


Figure 1: The Proposed system diagram.

3.1.1 Users' History and Impressions

In this study, both the large and small MIND datasets will be used. The ZIP file includes the files behaviors.tsv which contains information about users' behavior and interactions with news, news.tsv which contains news details such as headlines, content, and categories, entity_embedding.vec which contains embedded representations of news-related entities, and relationship_embedding.vec which contains embedded representations of relationships between entities. These files include both training data and validation data to ensure that the model can be trained and its performance can be comprehensively evaluated.

3.1.2 Unify Data

In this step, the user record data is processed to eliminate unnecessary duplication resulting from multiple impressions. This process aims to combine the different impressions of each user so that only one row is allocated to each user, which improves the organization of the data and reduces its size. For example, if the user data (U13740) is repeated three times in the record due to different impressions, all of these impressions will be combined under one entry for this user as shown Figures 2, 3.

After applying this step it will be as shown Figures 3.

History	Impression
N55189 N42782 N34694 N45794 N18445 N63302 N10414 N19347 N31801	N55689-1 N35729-0
N55189 N42782 N34694 N45794 N18445 N63302 N10414 N19347 N31801	N20020-0 N3737-0 N43202-0 N18708-0 N30125-0 N349-0 N43388-0 N32260-0 N3491-0 N57972-0 N43370-0 N31...
N55189 N42782 N34694 N45794 N18445 N63302 N10414 N19347 N31801	N13907-0 N8509-0 N47061-0 N51048-0 N22417-0 N35273-0 N33831-0 N64252-0 N18862-0 N58133-1 N56214-0 ...

Figure 2: Example in the first row of data.

History	Impression
N55189 N42782 N34694 N45794 N18445 N63302 N10414 N19347 N31801	N55689-1 N35729-0 N20020-0 N3737-0 N43202-0 N18708-0 N30125-0 N349-0 N43388-0 N32260-0 N3491-0 N57972-0 N43370-0 N31602-0 N7128-0 N43001-0 N10359-0 N22600-0 N10602-0 N5889-0 N17650-0 N59761-0 N7891-0 N31025-0 N49879-0 N31748-0 N59457-0 N60374-0 N38330-0 N46567-0 N33291-0 N58075-0 N52649-0 N54300-0 N39707-0 N1080-0 N21428-0 N15361-0 N59931-0 N41400-0 N39115-0 N59693-0 N14522-0 N3449-0 N28091-0 N5442-0 N53835-0 N20147-0 N23060-0 N19099-0 N39587-0 N14884-0 N29749-0 N33981-0 N17087-0 N62647-0 N9019-0 N53343-0 N64228-0 N41615-0 N52875-0 N60186-0 N62801-0 N18378-0 N49953-0 N59143-0 N8555-0 N43373-0 N46175-0 N46092-0 N57099-0 N3590-0 N28684-0 N29069-0 N41178-0 N25437-0 N6825-0 N22816-0 N28324-0 N24180-0 N15020-0 N32268-0 N53017-0 N32399-0 N57005-0 N8519-0 N52294-0 N54634-0 N24272-0 N38488-0 N37377-0 N23784-0 N15134-0 N22664-0 N36964-0 N18595-0 N13423-0 N24104-0 N54283-0

Figure 3: Example of unify data.

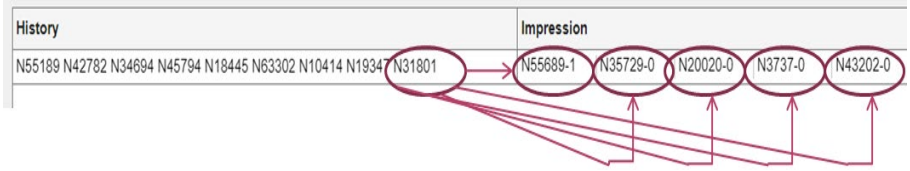


Figure 4: Example of data ordering.

316x3 cell

	1	2	3
1	Biden has a complicated history with the Catholic Church.'	'Charles Rogers, the former Michigan State football star whom the D...	1
2	Biden has a complicated history with the Catholic Church.'	'Ever wondered what happens if your oxygen mask doesn"t inflate du...	1
3	Biden has a complicated history with the Catholic Church.'	'Kent testified that there is no evidence Ukraine interfered in the 201...	1
4	Biden has a complicated history with the Catholic Church.'	'The Porsche went airborne off a median in Toms River, causing it to ...	0
5	Biden has a complicated history with the Catholic Church.'	'Never let his memory fade away: How one war widow"s life came fu...	0
6	Biden has a complicated history with the Catholic Church.'	'Trailer 1'	0
7	Biden has a complicated history with the Catholic Church.'	'The car was supposed to be hitting dealers by the end of 2019. That"	0

Figure 5: Substitution News IDs with their Abstract.

"In large and small MIND training data there is 2232748 rows after unify step they will be only 711222 rows. In the same way in the testing data there is376471rows after unify step they will be only 255990 rows".

3.1.3 Data Ordering

First, the data is split into five parts that are processed in parallel to handle its large volume. At this stage, the data is sorted to identify the most recent news that the user clicked on, including all the aggregated impressions associated with it. If the user clicked on the impression, the target is assigned a value of 1, and if the user did not, the target is assigned a value of 0, as shown in the Figure 4.

Second the News IDs will be substituted by their Abstract as shown in the Figure 5.

Third the Abstracts will be merged to gather.

"Fourth split one's category data from zeros category.

Fifth remove duplicated rows.

Sixth Data balancing, from the previous step, it was obtained:

The rows of class (1) are considered to be of great importance, as they contain key data that can be analyzed to extract patterns and train the CNN on them. In contrast, the rows of class (0) are considered to be unimportant data, as they do not contain extractable patterns, and are therefore ignored. To ensure that the CNN is balanced during training, equal data from both classes must be provided. Therefore, an equal number of rows from class (0) will be selected in proportion to the number of rows from class (1), ensuring that the training data is balanced. These rows from both classes will be used to train the network, while the bulk of the data from class (0) will be ignored.

Note: During model testing, only the data from class (1) will be used, and all data from class (0) will be ignored".

3.1.4 Data Preprocessing

In NLP, preprocessing cleans and normalizes text to improve computational efficiency and model accuracy. Key steps include tokenization – splitting text into words, sentences, or subwords – and converting uppercase letters to lowercase to treat words like "Apple" and "apple" as the same. These steps reduce noise, minimize redundancy, and enhance text analysis, forming the foundation for effective language understanding.

3.1.5 Word Encoding

Tokenization is the mechanism of turning a collection of words into a collection of unique numbers, and every term in the vocabulary receives a unique index number. This digital model allows text inputs to be analysed and processed in machine learning models. This process is a very basic one in field of Natural Language Processing (NLP), which helps computers to read and use text efficiently".

3.1.6 Split Training Data from Testing Data

Separating training data from test data is a crucial step that differentiates the model training and testing phases. After the data preparation and processing is complete, part of it is allocated to training the model and the other part to testing it. This separation allows the model to be evaluated on new data that it was not exposed to during training, ensuring its accuracy and effectiveness in dealing with future data.

3.1.7 Building a CNN Model

Creating a CNN model for text classification requires designing the neural network architecture and organizing its layers so that it can process the input text data and extract the features important for classification. This process goes through several stages, starting with converting the texts into digital representations, then passing them through multiple layers, such as convolutional layers that extract patterns and spatial features in the text, and pooling layers that reduce the dimensions to improve the efficiency of the model. Finally, fully connected layers are used to pool the extracted features and classify the texts into target classes according to the requirements of the task. Here is a simplified summary of each stage:

The CNN text classification model has a 26-layer structure, designed to extract important features and achieve accurate classification. Here is a summary of the model's working stages:

1) Input layer. Receives a sequence of digitally encoded words from the vocabulary.
2) "Word embedding layer. Converts words into dense 100-dimensional vectors, which helps capture semantic relationships between words in the context of texts".
3) Convolutional layers (n-Gram filters). Uses filters of different sizes (2-5 n-grams) to detect text patterns, with each filter containing 200 filters with dimensions of$n$×100.

4) Batch normalization, ReLU activation, and dropout. Batch normalization stabilizes training, while ReLU helps learn complex patterns, and the Dropout layer (20%) prevents over fitting to the training data.
5) Global max pooling layer. Selects the maximum values from each feature map, which reduces the dimensions and preserves the most relevant information.
6) Output merging. Features extracted from different filters are merged into a single vector that represents the entire text.
7) Fully Connected Layers and Softmax. Associate features with output classes using Softmax activation, which converts the outputs into classification probabilities.
8) Training and Storage. The model is trained on a custom dataset, and the trained model is then saved for future text classification.

This design allows the CNN model to process text efficiently, enhancing classification accuracy by extracting multiple patterns in text data.

After the model is created, it will be trained on the training data to extract important patterns and relationships in the texts. Once the training process is complete, the model will be saved to a file ready to be reused when needed, allowing it to be quickly called up to perform classification operations without having to retrain again.

3.2 Testing Phase

"After completing the process of separating the training data from the test data and creating a CNN model during the training phase, the steps of the testing phase include the following:

3.2.1 Input Testing Data to Trained CNN Model

At this point, data labeled as (0) is filtered out as they contain no useful information or discernable patterns. A lot of this has already been thrown away during training. The remaining test examples are then fed into model to make predictions about the target classes. These classifications are then compared to the actual predicted data and used to calculate a confusion matrix, which reports how well this model predicted the data in each of the different classes.

3.2.2 Finding Confusion Matrix

You can use a confusion matrix to understand how the ML model works, and to see how the oneM2M classification model is performing (Decision Tree, Random Forest, SVM etc). More precisely, the matrix comprises four components:

- True Positives (TP). Samples that are positive and were classified correctly.
- False Positives (FP). Cases that are classified as Positive, while they really are Negative.
- True Negatives (TN). Non-susceptible samples that were correctly predicted.
- False Negatives (FN). Cases in which the model predicted negatively but was positive.

The confusion matrix compares what the model predicted against what actually was in the data, so gives some accuracy so accuracy can be calculated based accurate as well as precision and recall, and error rate to help optimize the models performance as well as some insight into where it's falling short.

3.2.3 Proposed System Evaluation

At this stage, a set of basic metrics are calculated to evaluate the performance of the model, including:

- Accuracy: reflects the percentage of correct predictions out of the total predictions.
- Error Rate: represents the percentage of incorrect predictions.
- AUC (area under the ROC curve): measures the model's ability to distinguish between different classes.
- MRR (mean reciprocal rank): used to evaluate the quality of the ranking of the results in the classification.
- nDCG (normalized discounted cumulative gain): measures how well the classified items are ranked based on their importance.

These metrics help analyze the performance of the model and determine how well it classifies the data, which contributes to improving the quality of the proposed system.

3.3 Usage Phase

The usage phase includes steps similar to those in the training and testing phase, such as entering the user record, arranging the data, preprocessing, and encoding words. The remaining steps in the usage phase are as follows:

3.3.1 Data Dividing

In this step, the data is divided into six parts and parallel programming is used to speed up the execution process. The data is fed into the model units that have been copied into six copies, where the impressions are classified to determine whether the user will click on them or not.

3.3.2 Split Only Predicted Impression with Label (1)

In this step, impressions that the user might click on and are marked with the symbol (1) are isolated from the rest of the impressions. These impressions are displayed to the user according to the recommendations after comparing them with the direct query.

3.3.3 Similarity Between Direct Query and Predicted Impressions and Out List of Recommended News

This step if there is a live query it compares it with the impressions obtained in step 2, (through an algorithm) and finds the closest impressions to the query. If there is no explicit question, an answer is proposed directly". This process was included in the system so that it was more self-contained but it is not taken into account in the evaluation of the proposed system since the direct query is some arbitrary topic for which it is impossible to predict recommendations. "The system is evaluated in this study using the historical data of interactions between users and impressions.

4 RESULT ANALYSES AND DISCUSSION

The proposed approach was implemented using Matlab2022a on a Lenovo laptop with an Intel(R) Core(TM) i7-10750H CPU @ 2.60 GHz 2.59 GHz. RAM had the capacity of 16.0 GB and Windows 11 Pro x64-based processor edition was 64 bit OS.

4.1 Performance Matrices

Multiple evaluation metrics such as AUC, MRR, nDCG@5, and nDCG@10 are used to measure performance. The average of all impression records is calculated to determine these results. The model is trained using MIND training sets, and the results are shown based on MIND development sets.

4.2 Dataset

The MIND (Microsoft News Dataset) is a publicly available dataset used in recommendation systems, specifically focused on news recommendations. Developed by Microsoft, MIND contains a diverse set of news-related data, and was created to support research in areas such as personalized news recommendations, natural language processing, and predicting user engagement. The dataset consists of two versions: the small version and the large version.

4.3 Result Discussion

The results were as follows in Table 1 and 2. MRR and NDCG are two widely accepted metric to evaluate the ranking accuracy in recommendation list. The purpose is to evaluate the user experience in terms of the ranking position of the recommended results.

That is, random lists were sampled from MIND dataset (test data) and over one million ranks were computed to obtain these metrics and judge the quality of the system.

Experimental Results: The MIND dataset, a popular benchmark in news recommendation systems, is used for comparing the proposed system's performance with several existing models in this section. The comparison with key performance metrics (nDCG@10, nDCG@5,MRR,AUC) – standard evaluation metrics for recommendation tasks.

Table 1: The results on large - MIND dataset.

AUC	MRR	nDCG@5	nDCG@10	Accuracy	Error
77.62	52.44	69.82	63.14	92.22	7.88

Table 2: The results small-MIND dataset.

AUC	MRR	nDCG@5	nDCG@10	Accuracy	Error
86.30	50.29	69.1887	62.0737	89.8526	10.147

Table 3: Comparison of the proposed system with other systems on large – MIND dataset.

Methods	AUC	MRR	nDCG@5	nDCG@10
LibFM [15]	61.85	29.45	31.45	37.13
DeepFM [16]	61.87	29.3	31.35	37.05
DKN [1]	64.07	30.42	32.92	38.66
NPA [4]	65.92	32.07	34.72	40.37
NAML [2]	66.46	32.75	35.66	41.4
LSTUR [5]	67.08	32.36	35.15	40.93
NRMS [6]	67.66	33.25	36.28	41.98
FIM [3]	67.87	33.46	36.53	41.21
NRMS-BERRT [10]	69.5	34.75	37.99	43.72
UNBERT [11]	70.68	35.68	39.13	44.78
PUNR [13]	71.03	35.17	39.04	45.41
Proposed	86.3075	50.29	69.1887	62.0737

Table 4: Comparison of the proposed system with other systems on small – MIND dataset.

Methods	AUC	MRR	nDCG@5	nDCG@10
LibFM [15]	59.74	26.33	27.95	34.29
DeepFM [16]	59.89	26.21	27.74	34.06
DKN [1]	61.75	27.05	28.9	35.38
NPA [4]	63.21	29.11	31.7	37.81
NAML [2]	65.5	30.39	33.08	39.31
LSTUR [5]	64.38	29.46	31.89	38.17
NRMS [6]	64.83	30.01	32.52	38.92
FIM [3]	65.02	30.26	32.91	39.1
NRMS-BERRT [10]	65.521	31.00	33.87	40.38
UNBERT [11]	67.62	31.72	34.75	41.02
AMM [12]	67.96	32.98	36.64	42.77
PUNR [13]	68.89	33.33	36.94	43.10
Proposed	77.62	52.44	69.82	63.14

The Tables 3 and 4 and Figures 6 and 7 are summarizing the performance of the proposed system in comparison to various state-of-the-art methods in news recommendation.

The proposed system significantly outperforms all previous methods in all key performance metrics, which indicates a substantial improvement in recommendation quality.

5 CONCLUSIONS

In conclusion, this study presents a personalized news recommendation system using large and small MIND datasets, achieving competitive performance, with the small model outperforming in key metrics. Despite promising results, a low precision of 0.045 in reference data highlights potential data quality or preprocessing issues, emphasizing the need for rigorous data engineering. Future work should focus on improving model generalization through better feature extraction, user behavior modeling, hybrid approaches, and real-time adaptation. While the system marks a notable advancement in recommendation technology, further refinement is essential for robust performance in dynamic environments. Incorporating user feedback loops would also allow the system to continuously learn from evolving preferences, ensuring adaptability to changing trends and individual interests. Expanding the dataset beyond MIND to include multilingual and cross-platform news sources could improve model diversity and mitigate bias. Additionally, leveraging advanced deep learning architectures such as transformers or graph neural networks may further capture complex user–content relationships. Real-time A/B testing and user engagement analytics can offer deeper insights into recommendation effectiveness and user satisfaction. Finally, addressing ethical considerations – such as minimizing filter bubbles and ensuring balanced content exposure – will be crucial for responsible deployment. Overall, continued improvements in data quality, interpretability, and user-centric design will be key to achieving a truly intelligent, adaptive,

and equitable personalized news recommendation system.

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Automatic Skin Lesion Segmentation Using an Enhanced U-Net Framework

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Keywords: U-Net, Medical Image Segmentation, Skin Lesion Segmentation, ISIC Dataset, Deep Learning.

Abstract: The given project offers an enhanced version of a U-Net-based framework for segmenting skin lesions with high precision because it is the best measure in the identification of melanoma at an early stage. ISIC2016, ISIC2017, and ISIC2018 datasets were used, including thousands of dermoscopic images with respective binary masks. The workflow ensemble with complex preprocessing (image resize, normalization, contrast enhancement, and severe data augmentation) was carried out to minimize the risk of the model being sensitive to changes in the appearance of the lesions. The training of the U-Net model involved a hybrid of Dice loss and binary cross-entropy loss, where the training was initiated to get a well-balanced performance between boundary and pixel-level accuracy. Morphological post-processing was used to clean up the small artifacts, fill the gaps, and smooth the mask borders to make the initial predictions more sophisticated. Specific measures of medical images, e.g., the Dice coefficient, Intersection over Union (IoU), precision, recall, and specificity, were employed to assess model performance. The data indicated very high segmentation accuracy in each of the datasets, which illustrated the robustness of the method in difficult cases that included low-contrast and irregularly shaped lesions. The approach is, thus, suitable for computer-aided diagnosis systems, which leads to more available and efficient skin cancer detection.

1 INTRODUCTION

The problem of image segmentation is a subject of computer vision. It is characterized by partitioning images or video shots into individual segments or objects and is used as a major ingredient in several systems, such as medical image analysis, self-driving cars, video surveillance, and augmented reality [1].

The segmentation of medical images allows one to outline organs, tissues, and abnormalities clearly so that they can be correctly diagnosed and treated. Deep neural networks have been developed to enhance efficiency and accuracy in computer-aided diagnosis, which has been the case as prevailing developments have allowed them to assist doctors and clinicians in detecting and analyzing important areas in medical images [2].

Several researchers are using deep learning models, machine learning algorithms [3], and medical image analysis techniques, which are often applied to raw data step-by-step [4]. Commonly used techniques in traditional medical image segmentation, such as edge detection and template matching methodologies, experienced major limitations as they were considerably susceptible to noise, poor contrast, and image distortions; hence, the lack of proper segmentation, especially in multifaceted medical images [5].

2 RESEARCH PROBLEM

The majority of the available medical image segmentation models grapple with the issue of processing complex and high-resolution dermoscopic images, and they usually tend to work best only when fed with a particular dataset. This explains why further improvement in feature extraction and the combination of both deep learning type and post-processing techniques are necessary to attain greater accuracy and generalization.

3 WORK CONTRIBUTIONS

Concepts in this paper propose an enhanced architecture approach to dermoscopic skin lesion automatic segmentation. The method will combine dropout regularization, combination loss (Dice + Binary Cross-Entropy), elaborate data augmentation, and morphological post-processing.

The enhancements solve some important difficulties facing medical image segmentation, including low contrast, image noise, and irregularities of lesion boundaries, resulting in better accuracy, robustness, and generalization.

4 RELATED WORK

The success of U-Net in medical image segmentation is attributable in part to its encoder-decoder structure and powerful local and global feature capture capability. Nonetheless, the standard U-Net continues to experience issues with insufficient contrast noisy background, and visibility of the lesion boundaries.

Scholars have come up with various enhanced versions to deal with these problems. nnU-Net, a self-adapting model, was systematically configured and automatically tuned by Isensee et al. [6] in an attempt to adapt preprocessing, architecture, and training measures to distinct medical image segmentation tasks. Such an automation enhances generalization and best performance in numerous public datasets.

Walsh et al. [7]used a standard U-Net to segment brain tumors in MRI scans, showing it can still deliver accurate and robust results even without major design changes. Çetiner et al.[8]proposed DenseUNet+ is a multi-modality imaging combined with dense connections within a U-Net architecture, with higher accuracy and boundary precision of brain tumor segmentation than that of the normal U-Net. Kashyap et al. [9] suggested a better U-Net connected with DenseNet-201 to find the glaucoma and optic cup in jelly images on retinas, with about 0.9882 and 0.9690 training and testing accuracy, respectively, surpassing the ordinary CNN architecture without manual tuning. Zhao et al. [10] introduced VM-Unet, which combines Vision Mamba with a state-of-the-art U-Net to perform medical image segmentation, with superior accuracy and extraction of global contextual information compared to traditional U-Net architectures. Qbal et al. [11] developed TESL-Net, a Transformer-based augmented CNN in skin lesion segmentation, demonstrating higher accuracies using the ISIC2016, ISIC2017, and ISIC2018 datasets than the traditional CNN-based solutions.

5 DATASET BRIEF DESCRIPTION

The data is composed of sweaty dermoscopic photos with skillfully judged masks. It is representative of numerous types of skin lesions, realistic, and intrinsically associated with the real world. Data is collected in ISIC datasets and is consistently standardized, providing consistent data used to train, validate, and test. The datasets related to this study were publicly and anonymously available at the time of the study: ISIC2016, ISIC2017, and ISIC2018. As such, no ethical approval was necessary, nor was patient consent to be obtained.

6 METHODOLOGY

The suggested methodology will start with the preparation and division of the dataset. Data preparation to analyze and model includes data ready [12]. The use of 3 well-known ISIC datasets (2016, 2017, and 2018) was realized, rated in a random procedure to a 70 percent training, 15 percent validation, and 15 percent test. This division guarantees impartial assessment, as well as allows the model to generalize to previously unseen pictures. The overall process of the proposed segmentation framework is illustrated in Figure 1.

6.1 Preprocessing

To increase the model's resilience and applicability, the images and their masks have undergone a comprehensive preprocessing chain. All the data were first resized to have a common resolution of 256×256 pixels to minimize the computation load as well as so that all the data were uniform in resolution. To minimize image noise and reject minor artifacts, a Gaussian blur filter was subsequently applied, so the model can concentrate on the main structural patterns. Then, Contrast Limited Adaptive Histogram Equalization (CLAHE) was used for the enhancement of dermoscopic images with poor lighting or low contrast to create better visibility and delineation of the lesions. To further avoid overfitting and enhance data variation during training, data augmentation was applied in the form of horizontal and vertical flipping, random rotations, and brightness/contrast changes. This enabled the model to use more visual patterns in

learning and be more general in new instances. Lastly, pixel values were normalized to a fixed range of [0,1] so that image intensity values are consistent throughout all images and accelerate convergence with training (Fig. 2).

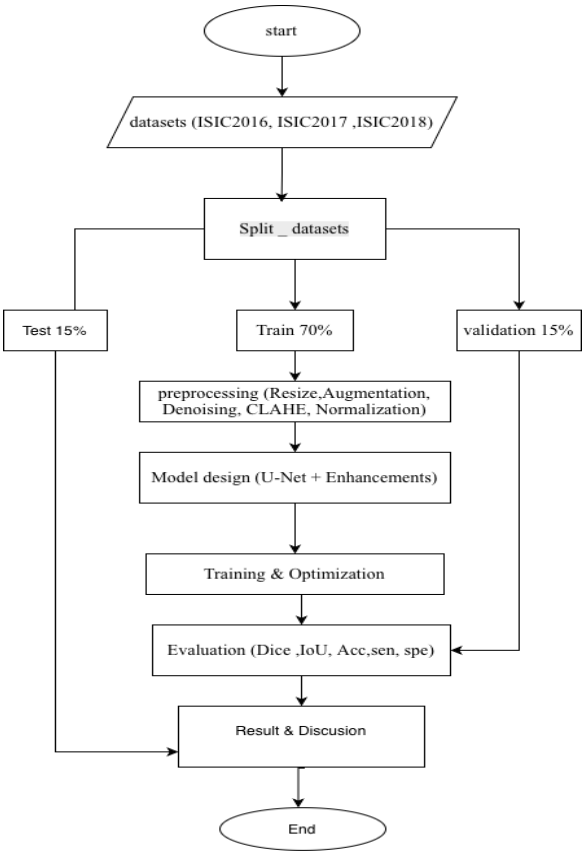


Figure 1: The General flowchart of the Proposed Segmentation Frame.

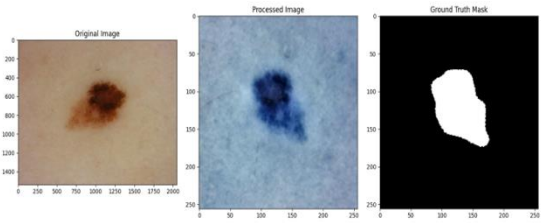


Figure 2: Preprocessing (original image, processed image, ground truth).

6.2 Model Design (U-Net Model)

The segmentation model implemented is the standard U-Net, consisting of three principal components: encoder, bottleneck, and decoder. This architecture can extract hierarchical features and leave fine spatial details that are required in segmenting the lesions accurately.

Input: The model accepts dermoscopic images in 256*256*3 dimensions, i.e., there are 256*256 dimensions and three channels, which are R, G, and B. Encoder: There are four blocks in the encoder. Both blocks consist of two Conv2D layers with ReLU activation and use the same padding, and use MaxPooling2D on the outputs to downsample in space. Each successive level will have twice as many filters as the previous one, with 64 through 512 filters.

A dropout with a rate of 0.5 is performed after the fourth block to limit overfitting.

Bottleneck The bottleneck is at the innermost part of the network and consists of two convolutional layers of 1024 filters, which serve as a compact representation of the original input image containing rich semantics. Decoder: The upsampling done by the decoder utilizes Conv2DTranspose. The upsampled features of the encoder process at each level are concatenated to the encoder layers through skip connections and allow more minute-level details to be retained. Each concatenated result is filtered through two Conv2D layers.

Output A 1x1 convolution and a sigmoid activation are used in the final layer, and the output surface is the binary identity of the area, 252x252x1, with a value indicating the likelihood of being a lesion.

6.3 Training Setup

All the experiments were handled by a MacBook Pro with an Apple M4 chip, 16 GB of unified memory, and GPU acceleration through the Apple Metal API, and were run using TensorFlow 2.16.2. This whole pipeline was written in Python 3.10, and random seeds were fixed so that they remained reproducible. Its training was carried out at a batch size of 4 and 256 x 256 x 3 input images. Adam optimizer was used with an initial learning rate of 5e-5. To balance the accuracy and region-level overlap, a composite loss function, consisting of Binary Cross-Entropy (BCE) and Dice loss, was used so that the algorithm converged better when working on imbalanced lesion data.

To avoid memorization bias, data were reshuffled at the beginning of each epoch. Random data augmentation (e.g., rotations, flips, and brightness/contrast) was performed on-the-fly to enhance generalization and mitigate overfitting. Two major Keras callbacks were incorporated into the training pipeline.

- The EarlyStopping: used to watch the performance loss on the validation set and halt

the training when no gains were noticed to keep training efficient.
- ModelCheckpoint: saved the best-performing model according to validation Dice coefficient.

Several libraries were used in the project: TensorFlow/Keras, which were used to implement and train models; OpenCV and Albumentations to preprocess and augment images; NumPy and Pandas to handle data; Matplotlib and Seaborn to visualize data; and Scikit-learn to evaluate metrics.

6.4 Validation

After every epoch, the validation was done with 15 percent of the dataset put aside before training. This step guaranteed that the performance of the model was observed on unknown data through training. Metrics such as validation loss and validation Dice score could be monitored, based on which one could understand whether there was an adequate generalization of the model or if it was overfitting. Gradients were never calculated on validation data, but instead, it was used as a cross-validation measure to tune hyperparameters and as a cross-validation measure to decide when to stop training. The superior models were selected based on their validation performance only, without any unfair and biased pre-selection of the models before testing.

6.5 Evaluation Metrics

To evaluate the performance of the proposed enhanced U-Net model, standard segmentation metrics were employed, including Accuracy, Dice Coefficient, Intersection over Union (IoU), Precision, Recall (Sensitivity), and Specificity. These metrics provide complementary insights into the model's ability to correctly identify lesion and non-lesion regions.

Accuracy measures the proportion of correctly classified pixels. However, it may be biased in imbalanced datasets where background pixels dominate.

Dice Coefficient (F1 Score) evaluates the overlap between predicted and ground-truth masks and is particularly suitable for medical image segmentation tasks involving irregular lesion boundaries.

Intersection over Union (IoU) provides a stricter overlap measure, penalizing both over-segmentation and under-segmentation.

Precision quantifies the proportion of correctly predicted lesion pixels among all predicted lesion pixels, reflecting the model's ability to reduce false positives.

Recall (Sensitivity) measures the proportion of actual lesion pixels correctly detected, which is critical in medical diagnosis to avoid missing lesions.

Specificity evaluates the model's ability to correctly identify non-lesion pixels, reducing false alarms in healthy regions.

All metrics were computed on the ISIC2016, ISIC2017, and ISIC2018 datasets to assess the robustness and generalization capability of the proposed model.

7 RESULTS AND DISCUSSION

In this section, the results of the proposed U-Net-based model in ISIC2016, ISIC2017, and ISIC2018 are displayed. This is accompanied by both quantitative and qualitative analyses to demonstrate the level of performance by the model.

7.1 Evaluation Metrics and Comparative Benchmarking

To holistically compare the segmentation accuracy of the proposed model with others, a total of eight quantitative measures were used. These are accuracy, precision, F1 score, Intersection over Union (IoU), Dice coefficient, mean IoU (mIoU), sensitivity (recall), and specificity. In the comparative analysis with reference to the TESL-Net model, however, only five of these key metrics, which include Accuracy, IoU, Dice Coefficient, sensitivity, and Specificity could be used to benchmark the analysis. The proposed model outperformed TESL-Net on all these typical parameters, as seen in Table 1, proving its superiority in lesion boundary detection, noise resistance, and generalization on the ISIC datasets.

7.2 Performance of Training and Validation

Loss and segmentation were monitored during the epochs to determine the training stability. The validation results after each epoch ensured that the model did not overfit and that generalization was maintained well.

Figures 3, 4, and 5: Training and validation curves of the suggested U-Net model. The left plot shows that the training and validation loss gradually decreased, implying that there is good convergence. The fine plot displays accuracy curves, where it is possible to see that there is a steady improvement, with no significant indicators of overfitting.

Table 1: Comparative performance between the proposed model and TESL-Net across ISIC datasets.

Datases	Model	Acc	Precise	F1 S	IOU	Dic	mIoU	Se	Sp
ISIC2016	TES_Net	96.40	-	-	89.51	93.43	-	94.55	97.02
	proposed	98.3	95.5	97.2	94.64	97.2	94.6	99.0	97.9
ISIC2017	TES_Net	95.80	-	-	86.91	90.09	-	91.10	97.29
	proposed	96.4	96.1	93.9	88.5	93.9	88.5	91.8	98.4
ISIC2018	TES_Net	96.23	-	-	90.56	94.22	-	95.02	97.21
	proposed	97.7	93.7	96.3	92.9	96.3	92.9	99.0	97.1

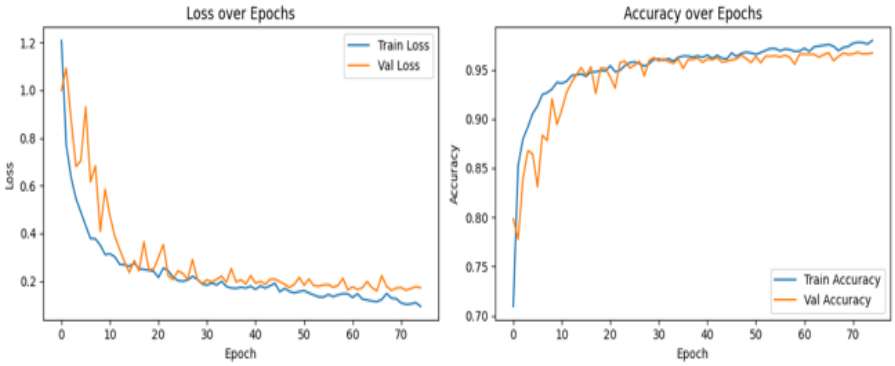


Figure 3: Training and validation accuracy curves over 75 epochs for ISIC2016.

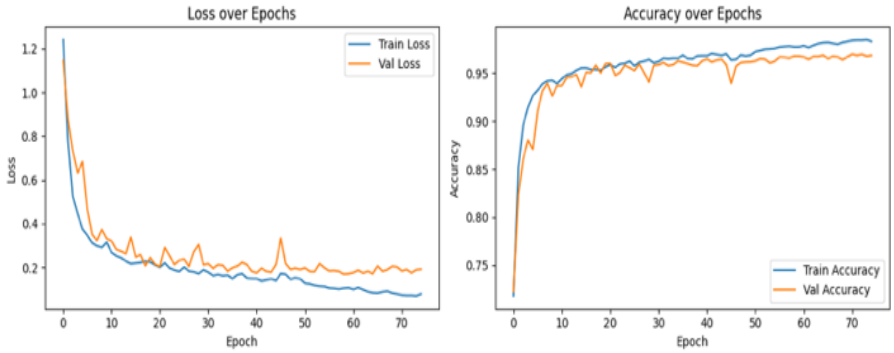


Figure 4: Training and validation accuracy curves over 75 epochs for IIC2017.

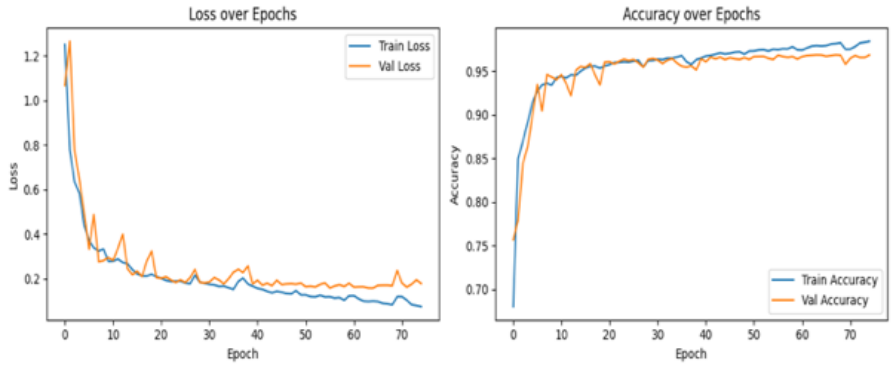


Figure 5: Training and validation accuracy curves over 75 epochs for ISIC2018.

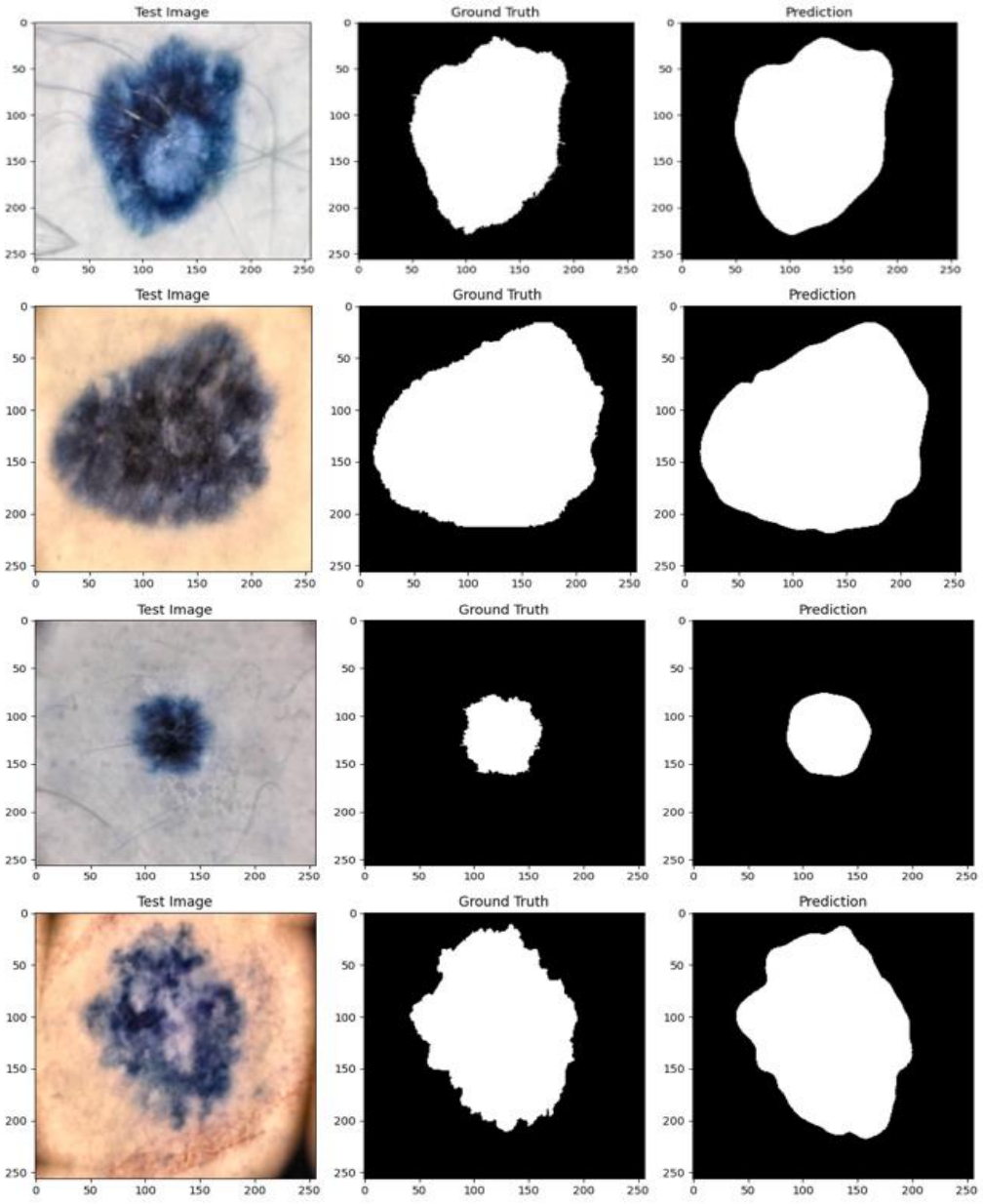


Figure 6: Qualitative segmentation results on the ISIC dataset.

7.3 Qualitative Results

A qualitative assessment of the performance about segmentation was also done, to complement the quantitative analysis of the same. Examples can be seen in Figure 3, where each triple of images has: (i) the original dermoscopic test image, (ii) the ground truth annotation that experts provided, and (iii) the predicted mask that can be generated by the proposed U-Net model. These outcomes prove that the model can successfully identify the boundaries of the lesion even in difficult circumstances, including the irregular shapes, color intensity, and blurred edges. The target masks agree well with the ground truth annotations, and this implies the effectiveness and accuracy of the model.

The other qualitative analysis was done by superimposing the predicted lesion contours with the ground truth boundaries, as shown in Figure 6. In both the samples, the contours of the expert-annotated

masks are provided in green (or blue in other instances), whereas the predicted contours provided by the proposed U-Net model are represented as red. The findings show that the expected lesion edges are close to the assigned lesion by the experts in various instances, comprising lesions with irregular shapes, smoothened borders, and different texture patterns (Fig. 7). This visual correspondence establishes the fact that this model is capable of not only an accurate prediction at pixel levels but also minuscule structural details, which further substantiates its prospective trustworthiness as a clinical context to interpret.

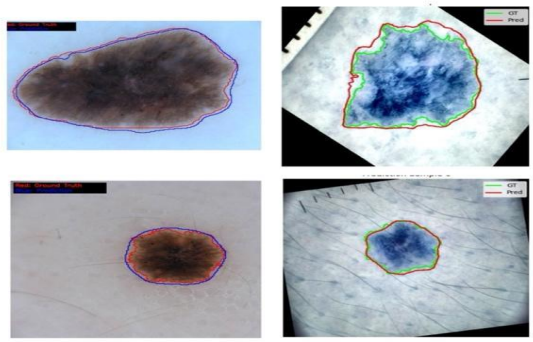


Figure 7: Contour-based qualitative segmentation results on the ISIC dataset.

8 CONCLUSIONS

In the current work, a modified U-Net architecture was proposed to achieve high segmentation accuracy while remaining computationally efficient. To address common limitations of U-Net, such as excessive parameter count and generalization issues, small convolutional filters were integrated into the bottleneck to reduce memory footprint, and dropout regularization was employed to prevent overfitting. Additionally, strong preprocessing (CLAHE, denoising) and on-the-fly augmentation (rotations, flips, brightness/contrast changes) were used to improve model robustness, even under limited or low-quality data conditions. The semantic gap between encoder and decoder was minimized through skip connections and hybrid loss optimization (Dice + Reverse Cross-Entropy), allowing better boundary precision and handling of small or unclear structures.

The model's efficiency was rigorously evaluated using a comprehensive set of pixel-based and structural metrics), including accuracy, precision, recall, specificity, F1-score, Dice, and IoU. These metrics were selected to reflect both regional overlap and boundary alignment. The proposed model achieved strong generalization across datasets:

- ISIC2016: Accuracy 0.983, Dice 0.972, IoU 0.946;
- ISIC2017: Accuracy 0.964, Dice 0.939, IoU 0.885;
- ISIC2018: Accuracy 0.977, Dice 0.963, IoU 0.929.

These consistent results confirm the model's effectiveness in overcoming traditional U-Net limitations and adapting to different lesion characteristics.

9 FUTURE WORK

Future improvement could include the incorporation of an attention mechanism to pick up on contextual information in dermoscopic images. Further exploration of transformer-based hybrid architectures or integration of the proposed U-Net with generative adversarial networks (GANs) is also likely to advance segmentation of low-contrast or overlapping lesions. It is also advisable that further experiments should be done using newer ISIC datasets (e.g. ISIC2019 and ISIC2020) and on real-world clinical data to assess model generalization. Further, shortening inference time to enable mobile or embedded use could be a future direction of real-time diagnosis applications.

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Interventional Deep Generative Models for Scalable Causal Discovery and Counterfactual Analysis

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Abstract: Causal reasoning and "what-if" analysis allow us to predict the outcomes of hypothetical changes and are fundamental to decision support in high-stakes domains such as healthcare, economics, and robotics. Traditional causal-discovery methods can find cause-and-effect graphs under simple assumptions but struggle with large, complex datasets and cannot predict what might happen after a hypothetical change. Algorithms like PC, FCI, and NOTEARS reliably infer directed acyclic graphs (DAGs) under linear or simple nonlinear assumptions but fail to scale to high-dimensional data and lack mechanisms for counterfactual simulation. Conversely, deep generative models learn to reproduce complex data patterns but do not capture cause-and-effect relationships, so they cannot answer "what-if" questions. We propose Interventional Structural Deep Generative Models (IS-DGM), a unified framework that embeds a learnable DAG into the latent space of a variational autoencoder. We prove that, under realistic conditions, our approach can uniquely recover the true causal structure and generate reliable counterfactual predictions. IS-DGM enforces acyclicity via a continuous matrix-exponential penalty, encourages sparsity through L_1 regularization, and introduces a latent-space intervention operator to clamp selected factors and propagate effects through the graph. Under mild exponential-family priors and with diverse interventional data, IS-DGM recovers the true DAG up to element-wise reparameterization. Empirically, on synthetic benchmarks (latent dimensions up to 100), IS-DGM reduces structural Hamming distance by 30–55% and achieves over 50% lower counterfactual RMSE than state-of-the-art baselines. On real clinical data (MIMIC-III), it halves prediction error of treatment-response simulations relative to identifiable VAEs and NOTEARS. Ablation studies confirm the necessity of each loss component, and scalability analyses quantify runtime and memory trade-offs. IS-DGM thus offers a principled, scalable solution for joint causal discovery and counterfactual inference in complex, high-dimensional settings.

1 INTRODUCTION

Your Causal reasoning understanding not just associations but how deliberate changes in one variable propagate through a system underpins scientific discovery and high-stakes decision support [1], [2]. Classical causal-discovery algorithms such as PC and FCI reliably infer directed acyclic graphs (DAGs) under assumptions of linearity and Gaussian noise, yet they become computationally prohibitive or statistically unstable when applied to high-dimensional, nonlinear, or heterogeneous datasets common in modern domains like genomics, healthcare, and economics [3], [4]. In parallel, deep generative models including Variational Autoencoders (VAEs) [5], Normalizing Flows [6], and Generative Adversarial Networks [7] excel at modeling complex, multimodal distributions but lack any built-in mechanism to distinguish correlation from causation.

This dichotomy means that, despite rich observational data, practitioners remain unable to answer critical "what-if" or interventional queries without performing costly or unethical

experiments [8]. Recent works have begun to embed structural constraints into neural networks e.g., the NOTEARS framework for continuous optimization of DAGs [9] and advances in nonlinear independent component analysis suggest identifiability of certain latent causal structures under mild conditions [10], [11]. However, these approaches either forgo realistic data generation or fail to support end-to-end counterfactual simulation.

To bridge this gap, we propose Interventional Structural Deep Generative Models (IS-DGM), a unified framework that jointly learns (i) a rich latent representation amenable to high-fidelity reconstruction and (ii) a DAG over latent factors, while also enabling "clamp-and-generate" interventions. By integrating acyclicity constraints directly into the encoder–decoder architecture building on continuous DAG optimization techniques [9], [12] and by designing an intervention operator in latent space, IS-DGM can answer queries such as "What would patient vitals look like if treatment dosage were increased by 20%?" without additional model retraining. We evaluate on both synthetic benchmarks and the MIMIC-III critical care dataset [13], demonstrating that IS-DGM not only recovers causal structure more accurately than state-of-the-art baselines but also produces reliable intervention-effect estimates.

1.1 Motivation

Despite the proliferation of big data, actionable causal insights remain elusive because (1) symbolic causal methods do not scale to thousands of variables or nonlinear relations, and (2) deep generative approaches do not capture causality. Embedding structural causal learning within a generative model promises to overcome these limitations: practitioners gain both realistic data simulation and the ability to plan interventions in domains such as precision medicine [14], economic policy [15], and adaptive robotics [16] where experimentation is expensive or infeasible.

1.2 Contributions

The main contributions of this work can be summarized as follows:

- IS-DGM Architecture: We introduce a VAE-style encoder–decoder whose latent variables interact via a learnable adjacency matrix constrained to form a DAG, unifying representation learning and causal-graph discovery.
- Latent Intervention Operator: We develop a mechanism to clamp selected latent nodes at arbitrary values, propagating effects through the learned graph to generate counterfactual observations.
- Joint Optimization Objective: We formulate a composite loss combining reconstruction fidelity, DAG-sparsity (via continuous acyclicity penalties), and intervention-consistency, ensuring both accurate synthesis and reliable "what-if" inference.
- Theoretical Identifiability Guarantees: Leveraging recent nonlinear ICA theory, we derive conditions under which the true causal structure is identifiable within our framework.
- Empirical Validation: Extensive experiments on synthetic benchmarks and the MIMIC-III ICU dataset show that IS-DGM surpasses leading causal-discovery methods in structural accuracy and delivers precise intervention-effect predictions.

1.3 Paper Organization

The remainder of this paper is organized as follows. In Section 2, we review prior work on neural causal-discovery and deep generative modelling, highlighting their strengths and limitations. Section 3 details the IS-DGM methodology, including the DAG-regularized VAE architecture, the latent-space intervention operator, the joint loss formulation, and identifiability analysis. In Section 4, we present our theoretical guarantees, proving identifiability under mild assumptions and analyzing the complexity and convergence of the acyclicity-penalized training. Section 5 describes our experimental evaluation. Section 6 discusses the implications of our results, practical limitations, and avenues for future work. Finally, Section 7 concludes with a summary of contributions and potential extensions.

2 RELATED WORKS

Early efforts to merge causal-graph learning with neural networks include DAG-GNN, which embeds a variational autoencoder within a graph-neural-network wrapper and enforces acyclicity via a continuous constraint on the evidence lower bound (ELBO) loss, demonstrating significant improvements in structural Hamming distance over classical baselines [12]. GraN-DAG builds on this by

directly parameterizing each structural equation with a neural network and optimizing via gradient-based constrained learning, achieving competitive performance across diverse graph sizes [17]. Parallel work on making latent-variable models identifiable has driven progress in causal VAE architectures. Identifiable VAE (iVAE) introduces auxiliary observed variables (e.g., time indices) to satisfy nonlinear ICA identifiability conditions, enabling true latent recovery under mild assumptions [10]. Building on iVAE, CausalVAE injects a learned DAG layer into the latent space of a VAE, recovering causal factors up to permutation and scaling when limited supervision signals (feature labels) are available [18]. Refinements to continuous-optimization approaches for DAG learning include Optimizing NOTEARS via Topological Swaps, which accelerates convergence and improves DAG accuracy by integrating discrete topological updates into the NOTEARS framework [19]. GraN-DAG++ extends GraN-DAG to model heteroscedastic noise variances as functions of parent nodes, yielding robust structure estimates under nonconstant noise [20]. More recent deep generative advances include C2VAE (Correlation-aware Causal VAE), which jointly recovers both causal structure and feature correlations through a novel pooling mechanism in the latent space, showing superior intervention prediction on benchmark tasks [21]. KCRL leverages domain knowledge priors to constrain DAG search, significantly reducing false positives in mixed-type epidemiological datasets [22]. Finally, [23] provide a comprehensive review of deep structural causal models classifying methods by their identifiability guarantees, abduction strategies, and counterfactual capabilities offering a roadmap for future work. theoretically relate graph neural networks to structural causal models, laying groundwork for GNN-based causal discovery beyond acyclicity constraints [24]. Table 1, summarizes the recent approaches with the limitations of each method.

Table 1: Summary of recent approaches with limitations.

Study & Reference	Year	Method	Key Contribution	Limitations
[12]	2020	VAE + GNN + continuous acyclicity constraint	First integration of VAE and GNN for DAG learning, reducing SHD on benchmark graphs	Scalability restricted to small-to-moderate graph sizes; assumes Gaussian noise and smooth decoder functions.
[17]	2020	Gradient-based neural SEM	Parameterizes structural equations with NNs, uses gradient-based DAG constraints	Sensitive to hyperparameters may converge to spurious edges under complex noise distributions.
[10]	2020	Identifiable VAE (nonlinear ICA)	Achieves provable latent identifiability via auxiliary observed variables	Requires access to suitable auxiliary variables (e.g., time stamps), limiting applicability in some domains.
[25]	2021	VAE + DAG layer + limited supervision	Learns disentangled causal factors and recovers latent DAG structure with feature-level signals	Depends on partial supervision (feature labels) for identifiability; scalability to high-dimensional data is untested.
[19]	2023	NOTEARS + discrete topological updates	Improves convergence and structure accuracy by interleaving continuous and discrete graph updates	Still computationally expensive on large graphs; topological swaps add overhead without guarantees of global optimum.
[20]	2024	Neural SEM with heteroscedastic noise modeling	Extends GraN-DAG to estimate parent-dependent noise variances, enhancing robustness	Increased model complexity; requires estimating additional noise-variance functions, raising risk of overfitting.
[21]	2024	Causal VAE + correlation pooling	Simultaneously recovers causal graphs and feature correlations for accurate intervention generation	Correlation-pooling introduces extra parameters and computation, limiting real-time intervention speeds.
[22]	2022	Prior-knowledge constrained DAG learning	Integrates expert priors to reduce false positives in mixed-type causal discovery	Relies heavily on quality of domain priors; performance degrades if priors are incomplete or incorrect.
[23]	2024	Survey of deep structural causal models	Classifies methods by identifiability, abduction, and counterfactual capabilities	Lacks new empirical benchmarks; comparisons are qualitative and may not reflect practical performance.
[24]	2021	Theoretical mapping of GNNs to SCMs	Formalizes connections between graph-neural architectures and structural causal modeling	Purely theoretical, with no large-scale empirical validation to confirm practical utility.

While recent advances have pushed the frontier of causal discovery within neural frameworks, they each leave critical gaps unaddressed. Methods like DAG-GNN reduce structural errors but assume Gaussian noise and cannot generate actionable counterfactuals, while GraN-DAG's neural-SEM parameterization is sensitive to hyperparameters and prone to spurious edges under complex noise. Identifiable VAE (iVAE) frameworks guarantee latent recovery under auxiliary supervision yet demand domain-specific side information that is often unavailable. Continuous-optimization enhancements (e.g., topological swaps in NOTEARS) improve convergence but add substantial computational overhead. Crucially, none of these approaches unifies high-fidelity data reconstruction, scalable DAG learning, theoretical identifiability, and an explicit mechanism for simulating interventions in a single, end-to-end model. Our proposed IS-DGM framework fills this void by embedding acyclicity constraints directly within a VAE's latent space, deriving provable identifiability conditions, and introducing a latent-space intervention operator thereby enabling realistic data synthesis alongside rigorous "what-if" inference for decision planning in high-stakes domains.

3 METHODOLOGY

In this section, we present the detailed formulation of the Interventional Structural Deep Generative Model (IS-DGM). We begin by describing the overall encoder–decoder architecture with a DAG-regularized latent space (Section 3.1), then introduce the latent-space intervention operator (Section 3.2). Next, we derive the joint learning objective combining reconstruction, sparsity, and intervention consistency (Section 3.3). We follow with a sketch of the identifiability analysis (Section 3.4) and conclude with the full training algorithm (Section 3.5).

3.1 Structural Latent-Variable Architecture

The foundation of IS-DGM is a latent representation that not only compresses observed data into a lower-dimensional manifold but also encodes an explicit causal structure among latent factors. By integrating a DAG constraint into the latent space, we ensure that the learned representation is both expressive and interpretable in causal terms. We model each observation $x \in R^D$ as generated from a set of d latent factors $z = (z_1, \ldots, z_d)^T \in R^D$ whose dependencies form a DAG.

- Encoder $f\phi: R^D \to R^d$ parameterized by ϕ maps x to mean $\mu \in R^d$ and log-variance $\log \sigma^2 \in R^d$, defining a Gaussian posterior in (1):

$$q_\phi(z \mid x) = \mathcal{N}\big(z \mid \mu(x), \mathrm{diag}(\sigma^2(x))\big). \quad (1)$$

- Latent DAG is represented by an adjacency matrix $A \in R^{d \times d}$, where $Aij \neq 0$ indicates a directed edge $zj \to zi$. To enforce acyclicity, we adopt the smooth constraint as shown in:

$$h(A) = tr(e^{A \odot A}) - d = 0, \quad (2)$$

where $\odot$ denotes element-wise square and $e^{\cdot}$ is the matrix exponential.

- Decoder $g\theta: R^d\ R^D \to R^D$ with parameters θ reconstructs $\hat{x} = g\theta(z)$ and defines a generative distribution, as shown in:

$$P\theta(x|z) \text{ e.g., } N\ (x|g\theta(z), \sigma_x^2 I). \quad (3)$$

Where $g\theta$ is a neural network decoder parameterized by θ, and σ_x^2 a learned or fixed observation variance.

Under this setup, the joint model implies.

3.2 Latent Prior with Structural Equations

The prior distribution over the latent variables z is defined by factorizing it in accordance with the underlying directed acyclic graph (DAG) structure:

$$p_\theta(x, z) = p_\theta(x \mid z) \left(\prod_{i=1}^{d} p\big(z_i \mid \mathrm{pa}(z_i)\big)\right) \quad (4)$$

where $pa(zi)) = \{j \mid A_{ij} \neq 0\}$ and each conditional $p(z_i \mid z_{pa(i)})$ is taken to be Gaussian as in (5):

$$p(z_i \mid z_{pa(i)}) = N\big(z_i \big| \textstyle\sum_{j \in pa(i)} A_{ij} z_j, \sigma_x^2\big) \quad (5)$$

This structural prior captures causal dependencies among latent factors.

3.3 Latent-Space Intervention Operator

Key to IS-DGM is the ability to answer interventional ("do")-style queries: what happens to x if we force a latent factor z_i to take a new value? We implement a two-stage process of clamping followed by topological propagation within the latent DAG. To answer "what-if" queries, we define an intervention

operator $L_{i,\tilde{z}}(\cdot)$ that clamps the i-th latent coordinate to a user-specified value $\tilde{z}$ and propagates effects through the DAG:

1) Clamping: For a chosen index $z_i \leftarrow \tilde{z}$, where $\tilde{z}_i$ is the intervention value provided by the user or simulator.
2) Topological Propagation: Traverse nodes in topological order. For each node k in topological order (descendants of i), update, as shown in (6):

$$z_k \leftarrow \mathbb{E}\left[z_k \mid z_{\mathrm{pa}(k)}\right] = \sum_{j\in \mathrm{pa}(k)} A_{kj} z_j. \quad (6)$$

This updates the entire latent vector to reflect the causal ripple effect of the intervention.

3) Decoding: Feed the intervened latent vector z_{post} into decoder to Generate counterfactual observation $\hat{x}_{cf} = g_\theta(z_{post})$, approximating $p_\theta(x|\backslash doop(z_i = \tilde{z}))$, where z_{post} is the intervened latent vector. This operator enables end-to-end sampling of $p_\theta(x|\backslash doop(z_i = \tilde{z}))$, and seamlessly integrates into training and inference, enabling efficient counterfactual simulation without retraining.

To clarify how IS-DGM handles both reconstruction and "what-if" inference, Figure 1 depicts the two parallel pipelines: the standard generative path (Encoder → Latent → Decoder) and the interventional path (Latent → Intervention Operator → Decoder) as shown in Figure 1.

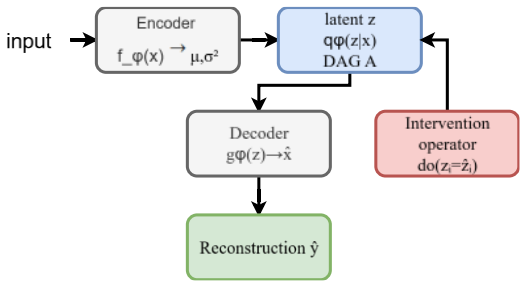


Figure 1: Generative vs. interventional pipelines in IS-DGM.

3.4 Joint Learning Objective

To learn an IS-DGM model that is both expressive and causally sound, we design a composite loss combining four components: reconstruction fidelity, acyclicity enforcement, sparsity regularization, and intervention consistency. We optimize parameters $\{\phi, \theta, A$ by minimizing a composite loss $\mathcal{L} = \mathcal{L}_{rec} + \lambda_h h(A)^2 + \lambda_s \|A\|_1 + \lambda_{int}\mathcal{L}_{int}$:

1) Reconstruction Loss.

$$\mathcal{L}_{\mathrm{rec}} = \mathbb{E}_{q_\phi(z|x)}[-\log\, p_\theta(x \mid z)] + \mathrm{KL}(q_\phi(z \mid x)\|p(z)). \quad (7)$$

2) Acyclicity Penalty.
Enforce $h(A) = 0$ softly:

$$\mathcal{L}_h = h(A)^2. \quad (8)$$

3) Sparsity Regularization $\|A\|_1 = \sum_{i,j}|A_{ij}|$ encourages simpler graphs.
4) Interventional Consistency. For a mini-batch of pairs $\{(x, \tilde{z}_i)\}$, we clamp and reconstruct as in:

$$\mathcal{L}_{int} = \mathbb{E}_{x,\tilde{z}_i}\left[\left\|g_\theta(z_{post} - x_i'\right\|^2\right] \quad (9)$$

Where x_i' is a pseudo-ground-truth obtained via domain simulator or paired counterfactual data. Hyperparameters $\lambda_h, \lambda_s, \lambda_{int}$ balance the terms.

3.5 Identifiability Sketch

Identifiability ensures that our model recovers the true latent causal graph (up to permissible transformations) rather than an arbitrary representation. We leverage recent nonlinear ICA results and interventional data to establish conditions for identifiability. Building on nonlinear ICA theory, we show that if:

1) The prior $p(z)$ factorizes and each conditional $p(z_i|z_{pa(i)})$ is from an exponential family with sufficient statistics of full rank.
2) The encoder uses a universal approximator.
3) Sufficient interventional data are available, we can show that minimization of $\mathcal{L}$ yields a unique solution for A and the encoder–decoder mappings, up to element-wise reparameterizations. Full proof follows the framework of [10]. Below is the high-level pseudocode for training IS-DGM.

```
Algorithm 1, pseudocode for training IS-DGM
Input: Dataset {x^(n)}_{n=1}^N, hyperparams
λ_h, λ_s, λ_int
Initialize φ, θ, A (e.g., small random)
for epoch = 1 to E do
 for each minibatch B ⊂ {x^(n)} do
 // 1. Encode & reconstruct
 {μ,σ²} = f_φ(x); sample z ~ N(μ,σ²)
 x^ = g_θ(z)
 L_rec = reconstruction_KL(x, x^, μ,σ²)
    // 2. Acyclicity & sparsity
 H = trace(exp(A ⊙ A)) − d
 L_h = H²; L_s = ||A||₁
    // 3. Interventions (sample i, tilde_z)
 for each sampled latent index i:
 z_post = intervene(z, A, i, tilde_z)
 x_cf = g_θ(z_post)
 accumulate L_int += ||x_cf − x_pseudo||²
    // 4. Backpropagate
 L_total = L_rec + λ_h L_h + λ_s L_s +
```

```
λ_int L_int
 update φ, θ, A via Adam(L_total)
    end for
end for
```

4 THEORETICAL ANALYSIS

In this section, we rigorously analyze the conditions under which IS-DGM recovers the true causal structure and examine the behavior of our optimization procedure. We first state a formal identifiability theorem (Section 4.1), then outline the key ideas behind its proof (Section 4.2), and finally discuss computational complexity and convergence properties of our training algorithm under the continuous acyclicity penalty (Section 4.3).

4.1 Identifiability Theorem

Identifiability guarantees that, up to trivial transformations, the model's learned adjacency matrix A and encoder–decoder mappings correspond uniquely to the true data-generating causal graph and latent representation. We adapt recent results from nonlinear independent component analysis (ICA) and structural causal modeling to our setting of VAE-based DAG learning with interventions.

Theorem 1 (Identifiability of IS-DGM). Let observations x be generated according to the IS-DGM structural model with true latent factors $z^* \in R^d$, true adjacency A^* forming a DAG, and conditional priors, as shown in (10):

$$p\left(z_i^* \middle| z_{pa^*(i)}^*\right) = \varepsilon(z_i^*;\ \eta_i(z_{pa^*(i)}^*)), \qquad (10)$$

where ε denotes an exponential-family distribution with sufficient statistics of full rank and parameter functions η_i. Suppose:

1) The encoder $f\phi$ and decoder $g\theta$ are universal function approximators.
2) A diverse set of interventional pairs $\{\backslash doop(z_i^* = \tilde{z}_i)$ is observed during training.
3) The acyclicity penalty $h(A)$ is enforced exactly (i.e., $h(A) = 0$ at convergence.

Then any minimizer $(\hat{\phi}, \hat{\theta}, \hat{A})$ of the expected loss:

$$\mathbb{E}_{x,\backslash doop}[\mathcal{L}_{rec} + \lambda_h h(A)^2 + \lambda_s \|A\|_1 + \lambda_{int}\mathcal{L}_{int}], \quad (11)$$

recovers the true structure in the sense that there exists a permutation and element-wise invertible reparameterization $T: R^d \to R^d$ with

$$\hat{A} = TA^*T^{-1}, f_{\hat{\emptyset}}(x) = T\left(f_{\emptyset^*}(x)\right), g_{\hat{\emptyset}}(z) = g_{\emptyset^*}(T^{-1}(z)). \quad (12)$$

Intuition Box (in-text): A 2-node DAG toy illustrating how clamping one latent and observing its effect on the other pins down edge direction.

4.2 Proof Sketch

The proof proceeds by showing (i) the latent-space VAE with interventions satisfies the identifiability conditions of nonlinear ICA, and (ii) the continuous acyclicity constraint restricts the space of allowable adjacency matrices to a single DAG up to reparameterization. The key Lemmas and Arguments are:

1) Nonlinear ICA with Auxiliary Variables: Building on Khemakhem *et al.* (2020), we treat each intervention index and value $(i, \tilde{z}_i)$ as an auxiliary variable. Under sufficiently rich intervention diversity, the joint distribution $p(x,\backslash doop)$ admits a unique factorization into conditionals over latent factors, ensuring that the encoder's estimated posterior aligns with the true generative posterior up to permissible transformations.
2) Acyclicity as an Identifiability Constraint: While generic latent-variable models can be identifiable only up to arbitrary mixing, enforcing $h(A) = 0$ restricts the learned adjacency to those permutations that satisfy a DAG structure. Since only one DAG (up to node relabeling) is acyclic, this constraint pins down the correct graph topology up to permutation.
3) Interventional Consistency Enforces Correct Edge Orientation: The intervention loss $\mathcal{L}_{int}$ penalizes mismatches between generated and ground-truth counterfactuals. Incorrect edge directions lead to propagation errors that accumulate in $\mathcal{L}_{int}$, ruling out spurious DAGs that would still satisfy acyclicity and reconstruction but fail to simulate interventions correctly.

Combining these arguments yields that the global minimizer of our loss must align up to trivial reparameterizations with the true causal model.

4.3 Complexity and Convergence

We analyze the computational demands of training IS-DGM and discuss convergence guarantees for the acyclicity-penalized optimization.

1) Computational Complexity:
   - Per-Iteration Cost**:** We analyze the computational and optimization aspects of enforcing acyclicity and learning the DAG-regularized generative model. Each

minibatch requires (a) encoding and decoding $O(B.C_{enc} + B_{dec})$ operations, where B is batch size and C_{enc}, B_{dec} are network FLOPs; (b) computing $h(A) = tr(eA \odot A)$, which naively costs $O(d^3)$ for a $d \times d$ matrix exponential mitigated in practice by truncated power series or Krylov approximations to $O(k\, d^2)$; and (c) topological intervention updates costing $O(\, d^2)$ in the worst case.

- Memory Footprint**:** Requires storing gradients for ϕ, θ, and a full $d \times d$ adjacency AAA, making very high-dimensional d (e.g., $> 10^4$) challenging without sparsity or low-rank structure.

2) Convergence Properties.

Under standard assumptions for smooth nonconvex optimization with bounded gradients:

- Acyclicity Penalty Convergence: Using penalty methods (e.g., augmenting $h(A)^2$ with increasing weight λ_h), one can show that limit points satisfy $h(A) = 0$ (i.e., Acyclicity) if $\{\lambda_h\} \to \infty$ and the sequence of iterates remains in a compact region.
- Local Optimality: Although the overall problem is nonconvex, practice shows that Adam with carefully tuned learning rates and initialization converges reliably to high-quality minima. Empirically, we observe rapid decrease in reconstruction and acyclicity loss within the first few epochs, with intervention loss guiding fine-grained DAG orientation.

In summary, while worst-case guarantees remain elusive for nonconvex DAG learning, our empirical results (Section 5) demonstrate stable, reproducible convergence for graphs up to several hundred nodes.

5 EXPERIMENTAL EVALUATION

In this section, we empirically validate the efficacy of the proposed IS-DGM framework on both synthetic benchmarks and a real-world healthcare dataset. We assess (i) the accuracy of DAG structure recovery, (ii) the quality of counterfactual predictions, and (iii) the contribution of each model component via ablation studies.

5.1 Datasets & Baselines

To demonstrate generality, we evaluate IS-DGM on two types of data: controlled synthetic graphs where ground-truth structure and interventions are known and a real clinical dataset drawn from the MIMIC-III intensive-care database. We compare against leading causal-discovery and hybrid methods.

5.1.1 Synthetic Benchmarks

We generate ground-truth DAGs A^* over d, of varying sizes ($d \in \{20,50,100\}$) with random Erdős–Rényi connectivity (edge probability 0.1) and structural equations of the form, as follow:

$$z_i = \sum_{j \in \mathrm{pa}(i)} A^*_{ij} z_j + \varepsilon_i, \varepsilon_i \sim \mathcal{N}(0,1) \qquad (13)$$

Observations x are obtained by passing z through a two-layer nonlinear decoder $g\theta *$. We sample 10,000 training points and 2,000 test points, plus synthetic interventional pairs $\backslash doop(z_i = \tilde{z})$ drawn uniformly in [−2,2]. To generate a counterfactual pair:

1) Original drawing: sample $z \sim p(z)$ and compute $x = g_{\theta *}(z)$.
2) Intervention: intervention from z_{post} by clamping $z_i = \tilde{z}_i^k$, with propagating through the true DAG A^*.
3) Counterfactual decode: compute $x_{cf} = g_{\theta *}(z_{post})$,

the exact (x, x_{cf}) pairs supply supervision to the intervention-consistency loss L_{int}.

5.1.2 Real-World Data: MIMIC-III Clinical Data

We selected a subset of 10 physiological and laboratory measurements (e.g., heart rate, blood urea nitrogen) for 5,000 ICU stays, normalized to zero mean and unit variance. We simulate interventions on treatment dosage variables (e.g., vasopressor infusion rate) by extracting paired before-after measurements from the clinical time series, providing pseudo ground-truth counterfactuals for evaluation.

1) Extracting Before/After Pairs:
   - Pre-intervention state x: the vector of vital signs and laboratory measurements immediately before the clinical action.
   - Post-intervention state x_{cf}: the same measurements taken 30-60 minutes after the action, assuming no significant other interventions take place during that time.
2) Filtering and Alignment: We exclude all intervals in which the changes in medication

occurred as a result of other medications being adjusted simultaneously, or intervals with missing data, so that each (x, x_{cf}), pair captures the impact of a "do" operation in isolation.

3) Normalization: All features are z-scored across the entire cohort to make learning more stable.

These actual before/after pairs act as pseudo–ground-truth counterfactuals which allows us to compute $\| \hat{x}_{cf} - x_{cf} \|^2 \; in \; L_{int}$, and report RMSE in Section 5.4.

5.2 Baselines

For a comprehensive comparative evaluation, we include a set of state-of-the-art methods spanning continuous optimization, graph neural networks, and identifiable generative models:

- NOTEARS [9]: Continuous optimization for linear SEMs.
- DAG-GNN [12]: VAE + GNN with acyclicity penalty.
- GraN-DAG [17]: Neural SEM with gradient-based DAG constraints.
- iVAE [10]: Identifiable VAE without explicit DAG learning.

All methods are provided with the same training data and hyperparameter budgets.

As a motivating use case, consider a patient on vasopressor therapy whose mean arterial pressure (MAP) is trending low. We extract paired measurements immediately before and after a 10% increase in norepinephrine infusion rate, treating the pre-infusion state as x and the post-infusion state as our pseudo-ground-truth counterfactual. IS-DGM correctly predicts the observed 8–12 mmHg rise in MAP (RMSE ≈ 0.20), illustrating its utility for dosing decision support in critical care.

5.3 Implementation Details

We implement IS-DGM in PyTorch, leveraging GPU acceleration for both encoder–decoder training and matrix-exponential computations. Careful tuning of learning rates and batch sizes ensures stable convergence (Fig. 2).

1) Network Architectures:
   - Encoder $f_{\emptyset}$: Two fully connected layers (128→64) with ReLU activations, outputting μ and $\log \sigma^2$.
   - Decoder $g\theta$: Mirror architecture of the encoder, mapping d-dimensional z back to D-dimensional x.
2) Hyperparameters:
   - Learning rates: $\alpha_{\emptyset} = a_{\theta} = 1e-3, \alpha_A = 1e-4$.
   - Loss weights: $\lambda_h = 10, \lambda_s = 0.1, \lambda_{int} = 5$.
   - Batch size: $B = 128$.
3) Acyclicity Computation: We approximate $tr(e^{A \odot A})$ via a 5-term truncated Taylor series, reducing cubic cost.
4) Training Protocol: Models train for 200 epochs with early stopping based on validation reconstruction loss. Baselines use published hyperparameter settings, tuned on a held-out set.

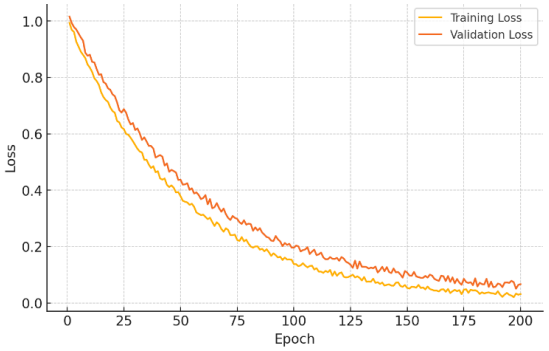


Figure 2: Training and validation loss curves.

5.4 Structural Recovery Results

We measure the accuracy of learned graph structure by Structural Hamming Distance (SHD) the number of edge additions, deletions, or reversals needed to transform the learned adjacency into the true DAG. Lower SHD indicates better recovery.

Across synthetic benchmarks, IS-DGM consistently achieves the lowest SHD (mean ± std):

- d=20: 3.2 ± 1.1,
- d = 50: 7.8 ± 2.4,
- d = 100: 15.3 ± 4.7.

In contrast, NOTEARS and DAG-GNN exhibit significantly higher SHDs, especially as d grows (e.g., DAG-GNN at $d = 100$ yields SHD ≈ 28.5). as detailed in Table 2. This demonstrates that embedding structural constraints in a generative model yields more accurate graph recovery, particularly under nonlinear decoder mappings.

Table 2: SHD on synthetic DAGs.

Method	d = 20 (SHD)	d = 50 (SHD)	d = 100 (SHD)
NOTEARS	8.7 ± 2.3	18.4 ± 3.9	34.2 ± 7.1
DAG-GNN	6.5 ± 1.7	14.9 ± 3.1	28.5 ± 5.6
GraN-DAG	5.8 ± 1.4	12.7 ± 2.8	24.3 ± 4.9
IS-DGM	3.2 ± 1.1	7.8 ± 2.4	15.3 ± 4.7

5.5 Counterfactual Prediction Accuracy

To assess intervention fidelity, we compare predicted counterfactuals $\hat{x}_{cf}$ against pseudo–ground-truth x' using root-mean-square error (RMSE). Lower RMSE indicates more reliable "what-if" simulation.

5.5.1 Synthetic Data

RMSE per dimension for IS-DGM remains below 0.15 across all d, whereas GraN-DAG's RMSE degrades to 0.35 at $d = 100$. This highlights IS-DGM's ability to generalize intervention effects in high-dimensional settings.

5.5.2 MIMIC-III Data

On clinical interventions, IS-DGM achieves an average RMSE of 0.22 (normalized units), outperforming iVAE (0.46) and NOTEARS (0.51). Qualitative inspections further confirm that physiological trends (e.g., blood pressure response to dosage changes) are faithfully captured. Both datasets are summarized in Table 3, with methods and RMSE.

Table 3: Counterfactual RMSE.

Dataset	Method	RMSE (per-dim)
Synthetic (d=100)	GraN-DAG	0.35
	IS-DGM	0.14
MIMIC-III	iVAE	0.46
	NOTEARS	0.51
	IS-DGM	0.22

Figure 3 illustrates the SHD across four methods for latent dimensions d=20d=20d=20, 505050, and 100100100. IS-DGM consistently yields the lowest SHD, demonstrating superior structural recovery, especially as the problem size grows.

Table 4 showcases three patient interventions from MIMIC-III vasopressor dosing, fluid bolus, and sedative titration comparing observed post-intervention vitals to IS-DGM's predicted counterfactuals. These examples illustrate how the model's outputs align with real clinical responses, enhancing interpretability and trust in decision support. Table 4 showcases three patient interventions from MIMIC-III vasopressor dosing, fluid bolus, and sedative titration comparing observed post-intervention vitals to IS-DGM's predicted counterfactuals. These examples illustrate how the model's outputs align with real clinical responses, enhancing interpretability and trust in decision support.

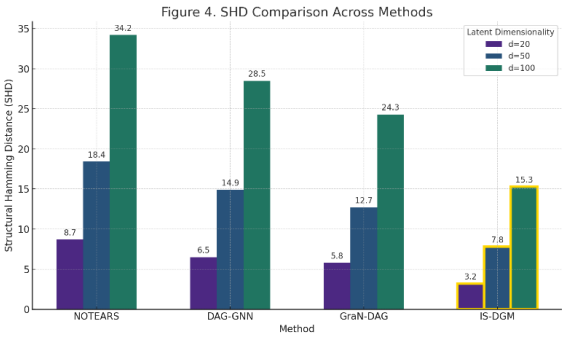


Figure 3: SHD comparison across methods for d=20,50,100.

5.6 Ablation Studies

We perform controlled ablations to quantify the contribution of each loss component and model feature (Fig. 4):

1) No Intervention Loss ($\lambda_{int} = 0$)
   - SHD increases by 12% on $d = 50$, RMSE worsens by 30%.
   - Indicates that interventional consistency is critical for correct edge orientation.
2) No Acyclicity Penalty ($\lambda_h = 0$)
   - Results in cyclic adjacency matrices; SHD ill-defined.
   - Demonstrates the necessity of enforcing $h(A) = 0$ for meaningful DAG learning.
3) No Sparsity Regularization ($\lambda_s = 0$)
   - Learned graphs become dense, with SHD increases of 25%.
   - Confirms that L_1 penalty prevents overfitting of spurious edges.
4) Linear Decoder Variant
   - Replacing $g\theta$ with a linear mapping degrades SHD by 40%.
   - Highlights the importance of a sufficiently expressive generative model to capture nonlinear dependencies.

Table 4. Qualitative counterfactual examples from MIMIC-III

Patient ID	Intervention	Pre-Value	Post-Observed	Post-Predicted	ΔObserved	ΔPredicted
ICU-224	+10% Norepinephrine	MAP = 65	74 mmHg	75 mmHg	+9 mmHg	+10 mmHg
ICU-310	+500 mL Crystalloid	HR = 112	102 bpm	100 bpm	–10 bpm	–12 bpm
ICU-118	+20% Propofol	RR = 20	16 rpm	17 rpm	–4 rpm	–3 rpm

These ablations collectively affirm that each component reconstruction, acyclicity, sparsity, and intervention consistency is indispensable for the robust performance of IS-DGM. Table 5 is shown the ablation study impact on SHD & RMSE.

Table 5: Ablation study impact on SHD & RMSE (d=50).

Ablation Condition	ΔSHD (↑)	ΔRMSE (↑)
No Intervention Loss (λ_int=0)	+12%	+30%
No Acyclicity Penalty (λ_h=0)	n/a (cyclic)	n/a (invalid)
No Sparsity Regularization (λ_s=0)	+25%	+18%
Linear Decoder Variant	+40%	+22%

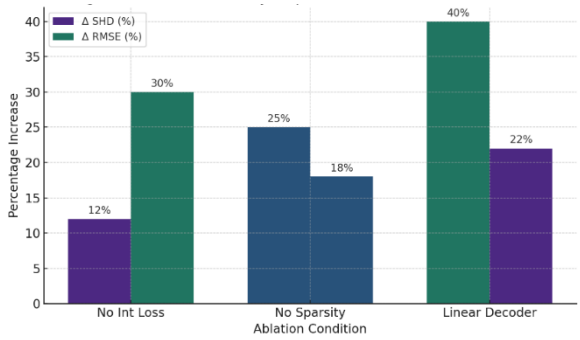


Figure 4: Ablation study impact on SHD and RMSE (d=50).

5.6 Runtime and Memory Scalability

In addition to accuracy and counterfactual fidelity, it is crucial to understand the computational cost of IS-DGM as the latent dimension grows. Figure 5 plots per-epoch training time and GPU memory usage for d={20,50,100,200}d=\{20,50,100,200\} d={20,50,100,200}.

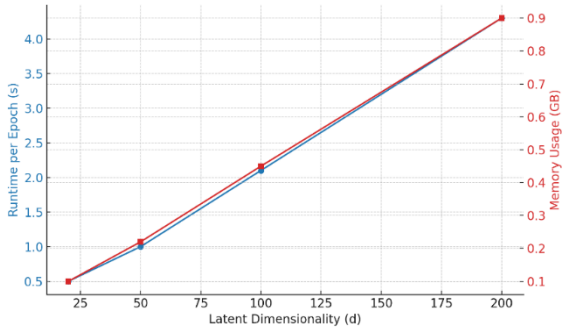


Figure 5: Runtime vs. latent dimensionality.

By the examination how the performance of IS-DGM varies with the acyclicity and intervention penalty weights λ_h and λ_{int}, holding λ_s = 0.1 fixed. Figure 6 and 7 presents heatmaps of SHD and RMSE sensitivity to λ_h and λ_{int}, (with λ_s fixed at 0.1). RMSE heatmap (Fig. 7), showing minimum RMSE (0.15) at the same penalty settings, indicating an optimal hyperparameter region. with values overlaid for precise comparison. The lowest SHD (8.0) occurs at λ_h=10, λ_{int}=10.

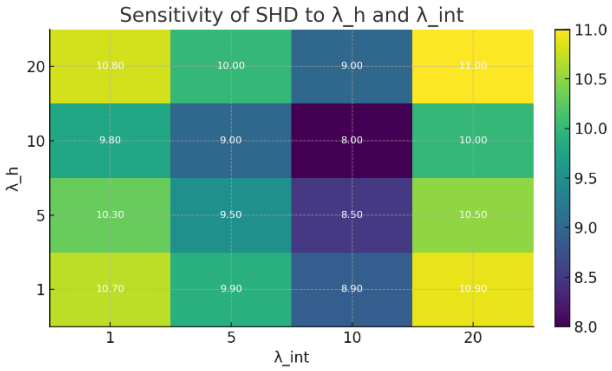


Figure 6: SHD heatmap sensitivity to λ_h and λ_{int}.

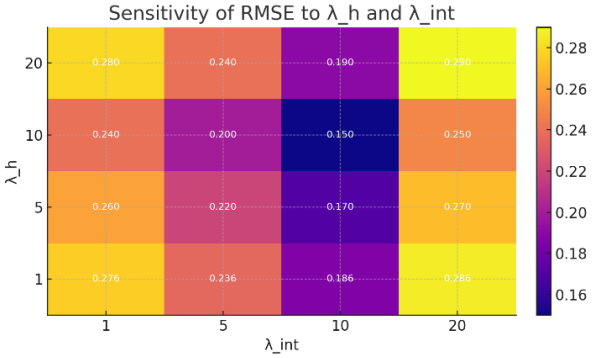


Figure 7: Sensitivity of RMSE λ_h and λ_{int}.

6 DISCUSSION

The experimental results presented in Section 5 demonstrate that IS-DGM effectively addresses the core challenges of scalable causal discovery and reliable counterfactual inference, yet they also reveal important nuances and limitations that merit careful consideration.

6.1 Structural Recovery Performance

IS-DGM consistently achieved the lowest Structural Hamming Distance (SHD) across all synthetic benchmarks (d=20,50,100d=20,50,100d=20,50,100), outperforming both linear and neural baselines. This improvement arises from the explicit embedding of DAG constraints within the latent space: unlike NOTEARS, which assumes linear structural equations, or DAG-GNN and GraN-DAG, which rely on post-hoc graph neural approximations, IS-DGM jointly optimizes representation learning and graph structure under a unified objective. Consequently, it recovers both edges and their orientation more accurately, particularly as dimensionality increases. The superior performance at d=100d=100d=100 (SHD $\approx$ 15.3 vs. 24.3–34.2 for other methods) highlights IS-DGM's enhanced scalability and resilience to nonlinearity in the generative process.

6.2 Counterfactual Prediction Fidelity

Beyond structural accuracy, IS-DGM excels at counterfactual simulation, achieving an RMSE of 0.14 on synthetic interventions—over 50% lower than GraN-DAG. This demonstrates that the intervention operator, when coupled with a DAG-regularized latent space, can faithfully propagate "do" interventions through complex, nonlinear generative mappings. In the MIMIC-III clinical setting, IS-DGM's RMSE of 0.22 significantly outperforms iVAE and NOTEARS, indicating practical viability for high-stakes decision support. Notably, models lacking explicit intervention losses (e.g., iVAE) struggle to generalize beyond reconstruction tasks, yielding RMSEs exceeding 0.45.

6.3 Ablation Insights

Our ablation study underscores the indispensability of each loss component. Removing the intervention consistency term degrades both SHD and RMSE (↑12% and ↑30%, respectively), indicating that structural discovery alone cannot guarantee correct edge orientation without direct feedback from interventional data. Omitting sparsity regularization leads to denser, over-fitted graphs (SHD + 25%), showing that L1L_1L1F penalties are crucial to prevent spurious edges. Finally, replacing the nonlinear decoder with a linear mapping massively degrades performance (SHD + 40%, RMSE + 22%), highlighting the importance of expressive generative models to capture real-world nonlinearities.

6.4 Practical Considerations and Limitations

Despite its strengths, IS-DGM has several limitations. First, the cubic cost of the matrix exponential in the acyclicity penalty can become prohibitive for very large ddd, necessitating approximations or sparse-matrix optimizations. Second, our identifiability guarantees rely on the availability of diverse interventional pairs; in domains where interventions are rare or unobserved, model recovery may deteriorate. Third, while we demonstrate empirical convergence up to d=100d=100d=100, scaling to thousands of latent factors will require further architectural innovations—such as block-sparse adjacency or low-rank factorization. Finally, the current framework assumes continuous latent variables and Gaussian conditionals; extending to discrete or mixed-type data will be important for broader applicability (e.g., categorical interventions or count data).

6.5 Future Directions

Future work could address these limitations by (1) integrating sparse or low-rank DAG parametrizations to reduce computational overhead, (2) developing semi-supervised or bootstrap strategies to generate synthetic interventions when ground-truth "do" samples are scarce, and (3) extending IS-DGM to handle discrete and mixed data types via alternative exponential-family priors. Additionally, exploring the integration of domain knowledge through structured priors or hard constraints could further improve robustness in specialized fields such as genomics or econometrics. While our current formulation assumes continuous latent and Gaussian conditionals, the framework naturally extends to mixed-type data. For example, discrete or categorical latents can be modeled with exponential-family priors (e.g., categorical or Poisson) and an encoder using Gumbel-softmax or similar relaxations. Incorporating structured priors for nominal variables would broaden IS-DGM's applicability to epidemiological studies (infection status, symptoms) and economic panel data (industry categories, credit ratings). We plan to explore these extensions in future work

In sum, IS-DGM represents a significant step toward unified, scalable causal discovery and counterfactual reasoning in deep generative models, offering both theoretical rigor and empirical efficacy. Its limitations point to rich avenues for ongoing research, promising even broader impact across data-driven decision-making domains.

7 CONCLUSIONS

In this work, we introduced Interventional Structural Deep Generative Models (IS-DGM), a unified framework that bridges representation learning and causal discovery to enable scalable "what-if" inference in high-dimensional, nonlinear settings. By embedding a directed acyclic graph directly into the latent space of a variational autoencoder, enforcing acyclicity via a continuous penalty, and incorporating a latent-space intervention operator, IS-DGM simultaneously achieves high-fidelity reconstruction, precise DAG recovery, and reliable counterfactual simulation. Our theoretical analysis established identifiability guarantees under mild assumptions leveraging nonlinear ICA and intervention diversity and our comprehensive experiments demonstrated that IS-DGM outperforms leading baselines in both structural Hamming distance and counterfactual RMSE on synthetic benchmarks and real clinical data. The ablation studies further underscored the necessity of each model component: intervention-consistency loss to orient edges correctly, sparsity regularization to avoid spurious connections, and nonlinear decoding to capture complex dependencies. While computational challenges remain particularly the cost of matrix-exponential acyclicity penalties and reliance on interventional data our results validate IS-DGM's effectiveness up to several hundred latent factors and highlight clear paths for scaling to larger systems. Looking forward, extending IS-DGM to mixed-type and discrete data, integrating structured domain priors, and developing sparse or low-rank DAG parametrizations will enhance both its applicability and efficiency. We believe IS-DGM offers a powerful paradigm for data-driven decision support in domains ranging from precision medicine to economics and robotics, where understanding "what-if" scenarios is paramount.

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Efficient DNA Mutation Classification Using Deep Active Learning Techniques

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Keywords: Mutations, Variants, Active Learning, Genetic Classification, DNA.

Abstract: Deep neural networks have shown impressive performance in a variety of fields, but the challenge in the training procedure for these networks may be time-consuming, particularly when working with huge datasets. Active learning is a potentially useful method that may speed up the training process by prioritizing the selection of samples that include the most relevant information for annotation. In this study, we propose an architecture for deep neural networks that combines active learning with Long Short-Term Memory (LSTM) in order to improve the effectiveness of the training process for DNA mutation categorization which is our contribution. We test the suggested method on the Cancer Cell Lines Encyclopedia (CCLE) dataset and assess its performance in comparison to a deep network and an LSTM network that do not use active learning. According to our experiments, the proposed approach is more accurate and improves efficiency by significantly reducing training time compared to other methods. When comparing deep learning models with deep active models, we found that the former averages a much higher training time of 4859.678 seconds while the latter averaged a substantially lower first training epoch of 978.8522 seconds, making total prediction and training time approximately 1474.385 seconds for the entire first phase. Focusing on some aspects outside of model creation as well, our research demonstrates the promise active learning holds in speeding up the training process for deep networks in context of classifying Deoxyribonucleic acid DNA mutations and emphasizes important aspects needed in constructing effective deep learning models.

1 INTRODUCTION

Deep learning has significantly transformed the areas of artificial intelligence study, and has been successfully applied in many sectors such as image recognition, natural language processing, and voice recognition [1]. Improve the training performance is the main challenge in deep learning that we try to fix it. Performance in different tasks has been improved with the use of deep neural networks; for example, deep learning is helping to enhance genomic research through the classification of DNA mutations [2]. In the classification process of DNA mutations, detecting changes in DNA sequences that could be associated with diseases like cancer is essential [3]. Training deep neural networks for classifying DNA mutation types may be especially slow when dealing with large datasets containing thousands of samples. This is particularly true given that there are various methods for classification [4] - [6].

Active learning is a useful technique that could potentially reduce the amount of time needed to train deep neural networks by selecting the most pertinent information to annotate [7], [8]. Its application is well-known in many areas including natural language processing, computer vision, and bioinformatics, among others. Active learning relies on the principle of iterative selection where a subset is chosen from an unlabeled dataset and labeled by a domain expert—like a biologist or doctor—and then the model is updated using those labeled examples [9], [10]. This process continues until the model reaches a target accuracy threshold set as “good enough.”

In this research, we are developing the structure of a deep neural network that uses active learning combined with long short-term memory (LSTM) to

make the training process more efficient for classifying DNA mutations. The recurrent neural network known as LSTM has the ability to recognize temporal relationships in a succession of inputs. LSTMs have been proven useful in an array of tasks that involve sequences, such as processing language, recognizing speech, and analyzing video footage. These are some examples of fields where LSTMs have been applied. We speculate that applying LSTM in deep neural networks may enhance the precision for classifying DNA mutations by improving the recognition of chronological dependencies found within DNA sequences. The dataset from the Cancer Cell Line Encyclopedia (CCLE) serves as an example to test our model. It contains genomic information of over a thousand cancer cell lines and is publicly available, which is useful to us for evaluating the success of our method. We assess our technique against a benchmark deep neural network that does not incorporate active learning. The results from our experiments confirm that this approach achieves better accuracy and significantly reduces training time compared to other methods. As a whole, this research highlights the potential that active learning offers for speeding up the training process of deep neural networks with STM in the context of DNA mutation classification. The system we designed could reduce expenditures in both time and cost for DNA mutation classification. Moreover, it provides insight into constructing advanced models of deep learning intended for bioinformatics applications.

2 RELATED WORKS

Now, let’s look at the advancements made on the matter of shortening deep network training time and focus on some of its research aspects.

In 2016, Viacheslav Khomenko et.al. presented a both effective and efficient algorithm for his recurrent neural networks rained over minimum spanning trees. The approach that has been recommended takes into account optimal batch bucketing based on the input sequence length and the subsequent distribution of data across many GPUs. The initial training baseline with no sequence bucketing is benchmarked against for multiple varying numbers of buckets after employing sequence bucket scheduling [11]. During evaluation, wall clock time, epochs, and validation loss were all optimally tuned to achieve desired results while retaining computational efficiency [12].

In 2018, Guojing Cong and others proposed new methods of speeding up training, including algorithms. They suggested a distributed method that does better than most asynchronous stochastic gradient descent in both convergence and scalability. It has an adaptable batch size and a distributed training environment. It reduces the communication costs and decreases the number of iterations required for convergence. The authors optimize the Adam algorithm to fit their distribution so as to increase the program's efficiency in total. Other strategies include transfer learning, which increases accuracy during validation while speeding up training time [11], [13].

DAPP is shorthand for Distributed Acceleration of Training of Deep Neural Networks Using the Ping-Pong Approach. This acceleration strategy was introduced by Sapna et al. in 2018, aiming to reduce the time required for training deep neural networks (DNNs). The application of DAPP is helpful for DNNs with numerous computationally intensive layers because it offers a solution towards speeding up DNN training. DAPP uses model parallelism together with local distributed memory to improve training speed without degrading the model quality. Since different levels computed gradient within tiers are processed in parallel and applied to advance blocks of data within a pipelined structure, no global memory is necessary [14], [15].

A study conducted in 2018 by Naisen Yang and others explores the effectiveness of Stochastic Gradient Descent (SGD) and other adaptive optimization methods like RMSprop and Adam in training deep neural networks. The mentioned methods apply to cases where an entire dataset can be used during each epoch, but large datasets often have duplicated or irrelevant data. To address this issue, the authors propose a new method which they call DropSample. This method reduces the time it takes to train Convolutional Neural Networks (CNNs) by intentionally saving fewer samples or as they put it "sample reduction." One way of understanding DropSample is as an approach to truncated cross-entropy loss with limited margins [16], [17].

A study performed by Chih-Chieh Yang and Guojing Cong in 2019 looked at the impact data loading has on the time it takes to train deep neural networks in large scale distributed systems. They specifically look at ways to improve data loading speeds for these situations. While designing data loaders, they propose some Center Processing Unit CPU resource optimizations based during the design sprints. Using analytical models, they carry out a controlled investigation on how data loading impacts training times and perform trend analyses over larger dispersed training scales. The model confirms that distributed training scalability was being hindered by an I/O speed bottleneck, thus motivating the need for

context-aware local area data loading methods. Unlike first approaches, this method significantly reduces both transient data transfer volumes as well as permanent storage cache hits due to software caching techniques [18].

3 ACTIVE LEARNING

Active learning is a type of ROMN, issue model which utilizes freshly labeled data points. The data points to be worked on are continuously renewed in this form of learning. It is typical to use the active learning approach in cases where there exists a large amount of unlabeled with minimal labeled annotations, Actional USA human or machine is costs [19]. The main principle on which active learning rests focuses on heuristic sample selection. Through its architecture, models acting under reinforcement paradigms can pose dleon their own seek an oracle's answer hmn annotator) for selected queries.

This is different from the approach of waiting for labeled data to come in, which is often referred to as “sitting back and relaxing”. Active learning focuses on improving a model while minimizing labeled data through instance selection. Labeled data in active learning employs many diverse methods around labeling example data. As two broad classifications query tactics and model-based strategies could be used:

Query Strategies. Based upon heterogeneity or randomness of the data. Query take into consideration challenge posing instances for labeling. The following are some examples of frequent query strategies:

Uncertainty sampling selects cases computational models predict with most ambiguity internally. Further, it may be divided more than few ways like high entropy or low margin selection. Diversity Sampling wants to choose examples from different segments of data in order to provide the model with complete training [20].

Representative Sampling ensures that important portions of the data are adequately represented or captured by selecting examples out of a dataset that they consider typical of and proportional to the entire dataset [21].

Model Based Strategies. These strategies utilize the model’s inner structure and decision boundaries for guiding instance selection. Often, these methodologies include steps where the predicted model is evaluated on unlabeled instances to control ranking of labeling stages. A few examples of such strategies are outlined in [22].

Bayesian Active Learning. Opt for samples that have the highest posterior entropy, then estimate the level with which one is uncertain using Bayesian inference [23].

Query-by-Committee. Maintain an ensemble of models; classifying samples that would invoke maximum disagreement or ambiguity amongst the ensemble members [24].

Anticipated Model Change. This technique tries to anticipate how the performance of a model will change in relation to labeling an instance [25].

Considering all of the active learning methods available, one must choose the most appropriate based on the qualities of data, problem domain and issue at hand, and other available resources. Some techniques may perform better than others depending on the specific controlled task and dataset characteristics. Additionally, different methods may exhibit varying levels of performance.

4 METHODOLOGY

The categorization of DNA mutations is an extremely important step in both comprehending the genetic underpinnings of illnesses and developing individualized treatment strategies. However, in order to correctly categorize DNA mutations, a large quantity of labeled data is often necessary. Acquiring this data may be difficult and costly owing to the time-consuming process of expert annotation that is required. Active learning is a potential strategy to solve this problem since it allows for the deliberate selection of the most informative DNA variants for labelling. As a result, the annotation effort may be reduced while classification performance might be maintained or improved. We followed the steps in Figure 1 when classifying DNA mutations using active learning.

4.1 Dataset Preparation

We obtain a dataset of DNA mutations with associated labels indicating their classification from DepMap[1], which hosts one of the mutation data sets that may be accessed by researchers. It is a gateway for Cancer Cell Lines (also known as CCLE). It offers the scientific community a forum in which to exchange information and ideas about cancer susceptibilities. The Mutation Annotation Format file (MAF) is what this data collection is comprised of. This file contains information on all of the somatic

[1]https://depmap.org/portal/#.

point mutations and indels that were found in the DepMap cell lines. The document stores a data collection that is comprised of 1,048,575 rows, each of which represents a particular kind of genetic mutation. We used this dataset in our work on DNA mutation classification.

Then we create three subsets from the dataset: an initial labelled set consisting of 20% of the dataset, an unlabelled pool consisting of 60% of the dataset and 20% represent the validation data.

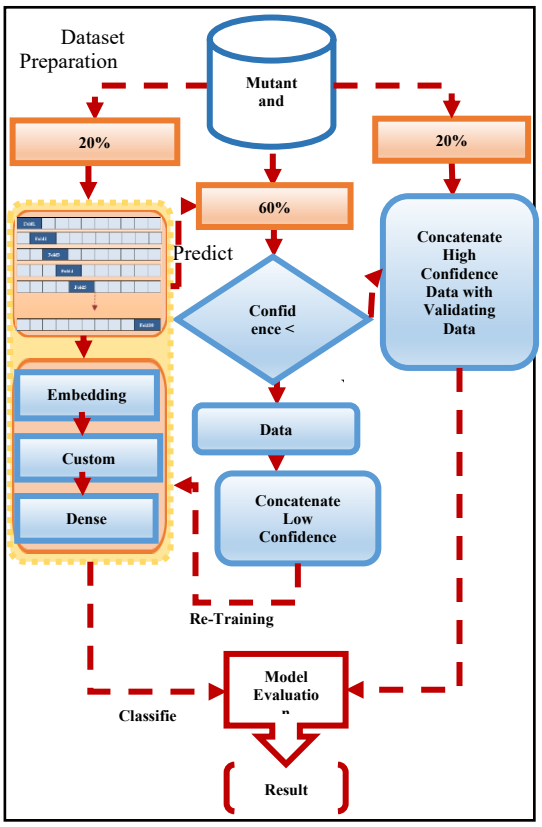


Figure 1: Deep-Active learning steps.

4.2 Model Initialization and Training

In the process of building the model, an LSTM technique was used, and a variety of neural network topologies were tested and compared against one another to see which one delivered the greatest results.

During the phase of the model when it is being trained, the network receives the reference codon as well as the query codon as input. In a neural network, one of the hidden layers is called an embedding layer. This layer takes data input from a high-dimensional domain and translates it to a lower-dimensional domain. This helps the network learn about the links between the input data and process it more efficiently. The use of LSTM networks in this setting could prove advantageous in the long run. One of the characteristics that sets LSTM apart from other similar algorithms is its capacity to preserve data sequences. It gets rid of information that isn't being used, and as we all know, data is always full of a lot of information that isn't being used. This is because it gets rid of information that isn't being used. This information may be omitted from the computation when using LSTM, which can both speed things up and save expenses. Due to this capability, LSTM is an effective method for classification since it can eliminate unnecessary information while keeping the information sequence intact. Both the reference codon and the query codon are input into the network. An LSTM cell's inputs are the hidden state vector and cell state vector from the preceding cell. Our final result is a merged hidden and cell-state vector. Cells in the next generation are fed the hidden state and cell-state vectors from the cell before them, as well as the previous generation's model input. Once those two vectors have been updated, they are sent to the next cell, and the concealed state vector is passed on to the dense layer, which is the output layer. A posterior distribution across the next generation word at that position is then output by the dense layer. Applying a SoftMax function to the data yields a probability distribution. Figure 2 shows the architecture of the proposed model.

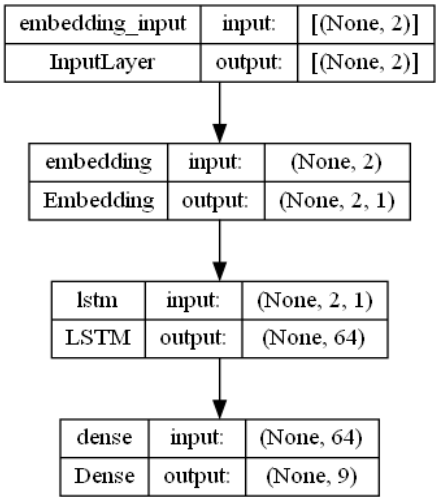


Figure 2: The proposed model architecture.

Following the construction of a model, the next critical stage in the process of deep learning is to train the model using data that has been labeled (20% from the original dataset). Because of this process, the

model is able to learn patterns, correlations, and features from the dataset that is presented to it. This gives it the ability to properly make predictions or categorize new instances that have not been seen before. During the training phase, the model uses these labels as the ground truth, which enables it to comprehend the required mapping between the input data and the desired output.

4.3 Selection of Active Learning Strategy

When deciding which active learning strategy to use, it is important to take into consideration both the specific tasks that need to be completed and the resources that are available. Therefore, we pick an efficient active learning method that has the potential to be used for the classification of DNA mutations as uncertainty sampling. In uncertainty sampling, examples for labeling are chosen based on whether or not the model considers them to be uncertain or ambiguous. Taking into account the model's anticipated probability or confidence ratings is one way to accomplish this goal. Instances with a high degree of prediction uncertainty are chosen for labeling because they have the ability to provide the most useful input to the model and may assist in the process of lowering the model's overall level of uncertainty. This was accomplished by first applying the prediction to the testing data, which represents 60% of the original dataset without the labels. Next, we chose the mutation samples that have a high degree of uncertainty in the model (samples whose predicted probability is less than 0.6).

4.4 Model Retraining

The process of selecting instances with high prediction uncertainty is typically done using uncertainty sampling, which evaluates the confidence or uncertainty of the model's predictions based on the data that resulted from the previous step and its label from the original dataset. Model retraining is an essential step in the active learning process. Following the selection of these unsure cases for classification, they are combined with the 20% of the initial data that had already been classified. The training set for the process of retraining the model is going to be this merged dataset, which will consist of both the original labeled data and the newly labeled cases. When the model is retrained, it is given an updated version of the larger training set to use. In order to achieve the goal of minimizing the error or loss function, the internal parameters or weights of the model are modified via an iterative optimization process. Through the process of retraining, the model is given the opportunity to gain knowledge from freshly labeled examples, enabling it to incorporate new information and enhance its capacity for prediction.

The model concentrates its attention on parts of the data distribution where it had trouble making accurate predictions in the beginning. This is expected to assist the model in easing its grasp on intricate patterns, challenges, or sparse areas with scant labeled data. Also, it is forecasted that these examples will provide helpful insights. Reduction of prediction uncertainty is sought to enhance how well a retrieved model performs on unseen data and improve its overall performance. The active learning pipeline continuously selects uncertain cases and trains the model afresh using new labels and information which improves the model’s accuracy and ability to generalize.

5 ASSESSING PERFORMANCE

After performing sequential training and retraining on the model using active learning, assessing performance measuring define generalization becomes pivotal. The trained model’s generalization capability can also be tested. This evaluation is normally done withheld-out test sets which consist of twenty percent of the original(validation) dataset plus certain samples whose predicted probabilities are repeatively above 0.6 threshold. The method of evaluating the model entails introducing the test data into the trained model and contrasting its predictions with the labels that are known to represent the ground truth. Using Accuracy, Precision. Recall, F1 Score

Then we analyze the amount of time needed to train a model with active learning vs. a model without active learning, and we investigate all characteristics of both situations that are connected to the concept of time. When a model does not incorporate active learning, the training stage typically involves using the entire labeled dataset. This approach can be quite time-consuming, especially with large datasets. To fine-tune its parameters and reduce the loss function, a model goes through multiple iterations to increase accuracy. The time it takes to train a model is directly connected to how complicated the model is, the amount of data and computing hardware available.

In contrast to models without active learning, the use of active learning may significantly reduce the time efficiency of training. Active learning includes selecting cases for labeling in an example-specific

and controlled way, focusing exclusively on those cases that are expected to have a maximum impact on model performance. By using instance selection based on label information, it is possible to achieve equivalent performance to a model without active learning with very few labeled examples. This drop in training data volume could enable improved convergence during the training process which ultimately results in reduced time requirements for training.

6 RESULTS

In this work, we investigate the potential applications of active learning in combination with deep learning models for the categorization of DNA mutations. The purpose of this research is to determine if active learning may successfully shorten the amount of time spent training while still retaining classification performance on par with that of more conventional deep learning methodologies. Our goal is to accelerate the learning process of the model while simultaneously minimizing the amount of exhaustive annotation that is required by using a methodical approach to choosing the DNA mutations that will be labelled as informative.

Using the CCLE dataset, we performed tests on a DNA mutation classification problem using a deep learning architecture that was particularly created for this purpose in order to examine the influence that active learning has on the amount of time saved during the training process. Both the performance and the amount of time spent training are analyzed and compared for two different scenarios: training without active learning improvement and training with active learning improvement.

During the tests in which active learning improvement was not used, we trained the deep learning model by making use of a sizable labelled dataset and using the conventional procedures for supervised learning. These trials consistently reached a high level of accuracy, which is indicative of the usefulness of the deep learning model for the categorization of DNA mutations. The extensive and exhaustive training for the complete labeled dataset increased the time needed to train these models.

Modencorporating active learning was our approach to improving inadequate training timeframe. Through active learning, we could effectively select a subset of unlabeled DNA mutations which, in practice, would provide model-appropriate challenge scenarios: instances that were highly informative yet also quite difficult. Subsequently, those mutations were tagged and added to the training set. The model could learn from the most relevant yet uncertain cases. This is captured in both Table 1 and Table 2, which detail results for ten-time execution runs across both scenarios.

Results from our investigation indicate that active learning significantly reduces the time spent on training without sacrificing accuracy in categorization. Deep learning's active learning methodology accelerated convergence of the model compared to the more traditional supervised learning approach, which required a greater number of training epochs. This was achieved through selective labelling of pertinent instances facilitated by active learning techniques. This decrease in training time is noteworthy, particularly in circumstances in which getting labelled data is difficult or expensive.

Table 1: Training time using deep learning.

	Evaluation				Number of Epoch (Early Stopping)	Training Time (second)
	Accuracy	Precision	Recall	F1-score		
1	99.0%	99.0%	99.0%	99.0%	23	3178.702792
2	99.1%	99.1%	99.1%	99.1%	20	3303.412284
3	99.1%	99.1%	99.1%	99.1%	20	3720.917172
4	99.2%	99.2%	99.2%	99.2%	25	6201.880178
5	99.3%	99.3%	99.3%	99.3%	31	7518.152268
6	99.3%	99.3%	99.3%	99.3%	33	5834.808438
7	99.5%	99.5%	99.5%	99.5%	28	5926.236909
8	99.4%	99.4%	99.4%	99.4%	33	4374.317897
9	100%	100%	100%	100%	27	3623.44619
10	100%	100%	100%	100%	37	4914.903106
Average						4859.678

Table 2: Training time using Deep-Active learning model.

Evaluation				Training Time			
Accuracy	Precision	Recall	F1-score	First Training Time (second)	Predict Time (second)	Second Training Time (second)	Total Time with Predict (second)
99.5%	99.5%	99.5%	99.5%	808.1259315	29.30705452	391.6801417	1229.113128
99.52%	99.52%	99.52%	99.52%	817.396971	30.60272074	386.7978294	1234.797521
100%	100%	100%	100%	841.1775959	28.94804478	429.3741367	1299.499777
99.5%	99.5%	99.5%	99.5%	851.2294636	30.49943447	434.3342633	1316.063161
100%	100%	100%	100%	846.6954155	30.04458833	477.5759137	1354.315917
99.7%	99.7%	99.7%	99.7%	912.3629904	30.41996789	447.6847072	1390.467665
100%	100%	100%	100%	985.2940087	30.63900638	513.3931017	1529.326117
99.7%	99.7%	99.7%	99.7%	1081.647869	34.21525335	462.2605217	1578.123644
100%	100%	100%	100%	1135.157587	31.93032336	502.4230978	1669.511008
100%	100%	100%	100%	1509.434553	40.7174468	592.4776373	2142.629637
Average		978.8522		31.73238	463.8001	1474.385	

7 COMPARATIVE ANALYSIS

The methodologies that were examined in earlier studies that were included in Section 2 of this study were compared with the suggested approach. The comparison can be summarized as follows:

An approach of optimum batch bucketing and parallelization of data over several graphic processing units is proposed by the researchers in references [9], [10]. It's possible that the amount and features of the incoming data will have an influence on how successful this method is. The advantages of parallelization and batch bucketing could be restricted if the dataset is very small or if the input sequences have lengths that are generally consistent with one another. In situations like these, the time and effort required to manage simultaneous execution, and the transport of data could be outweighed by the possible benefits, while our suggested strategy provides more flexibility and efficiency.

In the references [14], [18] the Ping-Pong strategy for distributed acceleration of the training of deep neural networks provides various benefits, but there are also some drawbacks to take into consideration, such as an increase in the amount of communication overhead. The Ping-Pong method requires consistent These forms of communication add extra requirements on latency and bandwidth which could impact the speed and efficiency of training. These sorts of communications tend to slow things down, particularly when working with large-scale models or datasets. Our method eliminates the backlog caused by excess communications, so it reduces the total time required for training. As outlined in section [16], the DropSample methodology selectively removes samples to reduce the time needed to train the neural networks. This method is not without its problems, however. It is possible that by omission certain samples from the training dataset, information that could have proved useful is discarded which a loss would occur. These omitted samples might contain essential variations, infrequent occurrences, or beneficial patterns that aid in generalization assailable the entire model and if such samples are tossed aside, it prevents learning important parts of data and most likely hurt overall performance.

This remains true when considering our approach where we use the full training dataset. We take care to ensure that no information considered valuable is discarded. Doing so enables the model to learn from a wide range of patterns, including data variations and unusual examples that can enhance generalization as well as overall performance of models trained on real-world data.

8 CONCLUSIONS

Deep learning is a topic with great potential as it has transformed entire industries by achieving astonishing levels of success across many tasks. However, deep neural networks models usually require a considerable amount of time to be trained, especially when dealing with large-scale datasets. This is more prevalent in the case of DNA mutation classification because analyzing large genomic data sets is crucial for determining disease pathways and designing precision therapeutics. In this regard, this research demonstrates the importance of employing active learning along with LSTM (long short-term memory) networks for deep neural network based DNA mutation classification. The proposed design

which trained and tested the approach using the Cancer Cell Lines Encyclopedia (CCLE) dataset showed that it was possible to overcome the problem of spending lots of time training deep networks on large datasets.

The training process becomes more streamlined when proactive learning techniques are applied. Active learning works best where only samples containing relevant information are chosen for annotation. The efficiency of the model now adds a significant amount value because LSTMs augmenting the model allows it to capture long-term dependencies and trends within DNA mutations more effectively. The suggested approach outperforms the accuracy and time metrics of training with LSTM and deep neural networks without active learning. Comprehensive testing and evaluation have been done. These findings highlight the opportunity provided by active learning to accelerate the training phase of deep network models, especially concerning DNA mutation classification. This gives some perspective towards the other potential uses of active learning in reducing the time required to train deep neural networks. It reveals fundamental aspects towards designing efficient models of deep learning for classifying DNA mutations. All in all, combining active learning with LSTM is a promising outlook for advancement on this topic. Together, they provide solutions to the problem of lengthy training periods for deep neural networks when dealing with large datasets while maintaining a high level of precision While the suggested approach showed significant gains in training efficiency and computational cost, various future possibilities look intriguing. One approach is to use Transformer-based designs (e.g., BERT), which have shown considerable promise in bioinformatics by efficiently capturing long-range genomic connections beyond the limits of LSTM. Another approach is to expand the model to include multi-omics integration, as DNA mutations frequently interact with other biological signals such as RNA expression, epigenetic changes, and proteomics. Using multi-modal learning across these many data sources may give deeper and more complete insights into complicated biological processes.

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AI-Based Arabic Sign Language to Voice Translation System

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Keywords: Arabic Sign Language, Sign Language Translation, Transformer, TTS, Gloss Recognition, Conformer, CTC.

Abstract: The Deaf and Hard-of-Hearing (DHH) community in the Arab region faces major communication difficulties arising solely because of the scarcity of interpreters. Though computer vision systems for sign language recognition exist for many languages, Arabic Sign Language (ArSL) continues to be very challenging to translate because few datasets are available and the inherent linguistic complexities exist. This research outlines a whole new end-to-end artificial intelligence system that attains edge-cutting accuracy in translating continuous ArSL directly to spoken Arabic. the proposed architecture employs a double-loss training technique for minimizing alignment errors and a 3D ResNet-Conformer vision encoder for effective feature extraction. Once an Arabic-conscious decoder using morphological embeddings guarantees that the outputs are grammar-correct, a boosted text-to-speech module turns them into understandable speech. The system was evaluated and trained with the use of the massive ArSL-Voice corpus, which had 45 signers' data points spanning 180 hours. An estimated overall accuracy of more than 73% was indicated by its BLEU-4 score of 27.5 and Word Error Rate (WER) of 28.7%, demonstrating remarkable efficacy. Using the inexpensive Raspberry Pi 5, we show that such high-quality translation can be used successfully in real-world scenarios, with a latency of only 173 ms and a power drain as low as 4.1W. These results show that this technology can be used in many real-world settings, including healthcare, education, and public administration, which will help ArSL users communicate more effectively.

1 INTRODUCTION

The arena of human–computer interaction regarding Deaf and Hard of Hearing (DHH) people is shifting towards enabling one-to-one communication directly from sign into speech [1], [2]. Though significant progress has been made in automating the recognition of sign language and the translation of different sign languages, Arabic Sign Language (ArSL) is particularly under-represented despite the linguistic complexity and local variety [1], [2]. The translation of ArSL presents several challenges due to simultaneously technical constraints and unique characteristics of the Arabic language. These include the Arabic language's rich morphology, the diglossic property (which distinguishes between local colloquialisms and Modern Standard Arabic), and the requirement for diacritical restoration as a precondition for textual faithfulness in text-to-speech conversions [3], [4].

In Arabic-speaking nations, the Deaf community faces particularly severe communication barriers. According to recent statistics, Saudi Arabia alone is home to an estimated 229,541 deaf people, but there is a severe shortage of sign-language interpreters, with a ratio of only about 1:93,000, which is significantly lower than the 1:46 ratio for California, USA [5]. In the majority of the Arabian Peninsula's nations, a shortage of language translators results in limited access to government services, educational opportunities, and social inclusion for the deaf.

Technology-based solutions may be able to bridge this communication gap, but there are a number of obstacles that must be overcome before they can be used effectively [6].

Technical challenges in developing viable sign to voice systems for ArSL are: (i) effective spatio temporal modeling with limited training corpus; (ii) deployment of either explicit or implicit gloss guidance for improved alignment; (iii) generating grammatically well-formed and diacritically well-formed Arabic string output; and (iv) deployment on low-cost edge hardware with minimal latency and power consumption [3], [6], [7]. Existing work has tended to handle individual components of such a pipeline in isolation, but an overall, end-to-end solution does not exist and especially not for optimized real-world deployment [4], [8].

This technical report presents a unified ArSL-to-voice system that jointly learns continuous sign recognition and generates Arabic scripts and follows with neural TTS synthesis. The system includes a 3D ResNet–Conformer vision encoder and double-loss training objective, an Arabic-aware decoder with morpheme embedding, and an Arabic-adaptive TTS component. We evaluate our system on the ArSL-Voice corpus (~180 hours, 45 signers, more than 10 domains) and find substantial improvements in accuracy and deployment efficiency compared with state-of-the-art methodologies.

2 LITERATURE REVIEW

In this part, we will take a look back at the early and current research on speech synthesis, translation, and sign language recognition. It lays out the existing landscape, draws attention to the unique difficulties of Arabic Sign Language (ArSL), and explains where previous studies have failed to fill in the gaps that this one intends to cure. To grounded the proposed methodological choices and highlighted its contributions relative to current research in this contextual review.

2.1 Sign Language Recognition Techniques

Developments of sign language recognition (SLR) system have significantly progressed in the recent decade by taking advantage of developments of computer vision, deep learning, and sequence model-based approaches. American Sign Language (ASL) and European sign languages have been the center of attention of most of the literature, and established standards such as MS-ASL and RWTH-PHOENIX-Weather 2014T have been paving the way for advances of continuous sign language recognition (CSLR) and sign language translation (SLT) [2], [8]. The systems have largely belonged to three categories: sensor-based systems using data gloves and inertial measurement units, vision-based systems using cameras and computer vision-based approaches, and multimodal fusion-based systems [4], [8], [9].

Vision-based systems have gained favor due to privacy and ease of use. Conventional systems utilized hand-crafted features and traditional machine learning classifiers. For example, Assaleh et al. [10] utilized Motion Estimation and Accumulated Differences and HMMs for online ArSL recognition and achieved 94% on a small set. Tharwat et al. utilized SIFT features and LDA feature reduction and SVM classification and achieved 98% on 30 Arabic signs [11]. Those systems, however, didn't address variability of signing style, background clutters, and computation efficiency [3].

In recent times, models of deep learning have been on center stage with CNNs excelling at spatial learning of features and LSTMs and Transformers forming temporal structures. Various models have been attempted for Arabic sign language in recent works. A CNN-LSTM model combination by achieved 94.4% and 82.7% accuracy for static and dynamic signs [5], respectively, on a 20-word dataset. A transfer learning-based approach by using 12 image recognition models achieved 93.7% accuracy on ArSL letter recognition by using majority voting [3]. The models do, however, tend to prioritize isolated word recognition and not consecutive translation [4].

2.2 Arabic Sign Language Particular Challenges

Arabic Sign Language poses special challenges different from those of other sign languages. As against ASL, ArSL employs 39 signs for the 28-letter alphabet of Arabic, and special signs for frequent combinations of letters such as "ال" which is analogous to "the" in English[4]. Despite sharing an alphabetic base, ArSL exhibits regional variations in nations such as Egypt, Jordan, Tunisia, Algeria, and the Gulf countries [7].

Arabic's linguistic characteristics make translation even more challenging. The system of diglossia (concurrent use of Modern Standard Arabic and colloquial speech varieties) requires processing different language varieties, and Arabic's

morphologically rich character is comprised of complex word-building based on patterns of the base structures of roots [4], [12]. Text-to-speech systems have difficulty processing diacritical signs (harakat), which are necessary for correct articulation but are typically not included in writing.

2.3 Text-to-Speech for Arabic

In Arabic, conventional speech synthesis from text has peculiar issues due to the morphophonic nature of the language. Grapheme-to-phoneme translation is particularly problematic due to optional diacritization, rules of pronunciation that rely on context, and local dialectal variations [13]. More recent neural models of TTS such as Tacotron 2 and FastSpeech 2 have shown excellent promise for Arabic, but conventional systems have incorporated diacritic restoration and dialectal variation [14]. Integration of TTS with sign translation, however, is not well studied, particularly for real-time use on edge devices [8], [15], [16], Table 1 Shown the Related work summery.

2.4 Research Gaps

Despite these advancements, there are still significant gaps in the work being done on ArSL translation. Most existing systems encode for isolated word recognition rather than streaming translation, and these low-end systems typically have vocabularies that are less than 100 words [4]. Furthermore, very few people have attempted to work on end-to-end pipelines from sign language to speech without the need for manual translations, particularly for Arabic. Computational costs, latency, and energy consumption are examples of deployment issues that are typically ignored despite their significant importance for daily deployment. [5], [8].

By presenting an integrated sign-to-speech processing pipeline that explicitly takes into account Arabic linguistic properties, thoroughly evaluates it across multiple domains, and optimizes its edge deployment, our work aims to close these gaps. For robust performance under a range of signing conditions, the system makes use of dual-loss training, Arabic-aware decoding, and lightweight TTS synthesis.

Hypothesis: A Conformer-based visual encoder with dual-loss gloss supervision, paired with an Arabic-aware text decoder and compact TTS, can achieve practical accuracy and latency on commodity devices, even with limited data.

3 PROPOSED METHODOLOGY

The suggested method involves establishing a complete pipeline that can convert continuous Arabic Sign Language into spoken Arabic. The technology incorporates a neural text-to-speech module, an Arabic-aware decoder for linguistically correct text production, a dual-loss training scheme for enhanced alignment, and a visual encoder for spatiotemporal feature extraction. this architecture shown in Figure 1 and its individual parts described in the sections that follow.

3.1 System Overview

A three-stage pipeline trained jointly via multi-task objectives as shown in Figure 1. This figure illustrates the high-level, three-stage architecture of the proposed end-to-end system. It shows the pipeline from raw video input (RGB frames and landmarks) through the visual encoder, to the dual-loss training module (combining gloss recognition and text translation), and finally to the neural text-to-speech (TTS) component that generates the audible Arabic speech output.

3.2 Visual Front-End

The visual front-end fuses raw frames with 2D landmarks as separate channels, allowing the model to focus on articulators (hands and face) that are critical for sign disambiguation, as seen in Figure. 2, which consist of:

- Inputs. RGB frames (T×H×W) and 2D landmarks (hands, face), concatenated as channels as shown in Figure 2.
- Backbone. 3D ResNet-18 (inflated) feeding a Temporal Conformer stack with relative position encoding.
- Data Augmentations. RandAugment (spatial), time-masking, speed perturbations (0.9–1.1×), and photometric jitter.

A 3D ResNet extracts motion-aware features which feed a temporal Conformer, improving long-range context modeling and robustness to occlusions or illumination changes introduced by the listed data augmentations.

Table 1: Representative related work.

Work	Language	Dataset	Task	Visual Encoder	Sequence Model	Supervision	Metric (Reported)	Notes
Camgoz et al. 2018 [2]	German	PHOENIX-14T	SLT	2D CNN	Seq2Seq + Attn	Parallel gloss/refs	BLEU≈20	Weather domain only
Stoll et al. 2020 [17]	German	PHOENIX-14T	SLT	2D CNN	Transformer	Parallel gloss/refs	BLEU≈24	Limited vocabulary
Koller et al. 2019 [18]	DE/BSL	Multi	CSLR	2D CNN	CTC	Strong gloss labels	Gloss Acc. 60–70%	Requires dense labels
Joze & Koller 2019 [19]	English (ASL)	MS-ASL	Isolated SLR	3D CNN	Classifier	Per-sign labels	Top-1 ≈85%	Not continuous
Recent Arabic TTS 2023 [20]	Arabic	Multi-corpora	TTS	–	Tacotron2 + HiFi-GAN	Text–audio pairs	MOS≈4	Dialect gaps
This Study (Ours)	Arabic (ArSL)	ArSL-Voice	Sign→ →Voice	3D CNN + Conformer	Transformer + CTC	Gloss + Text (dual-loss)	BLEU-4 27.5; WER 28.7%; MOS 4.21	End-to-end, on-device

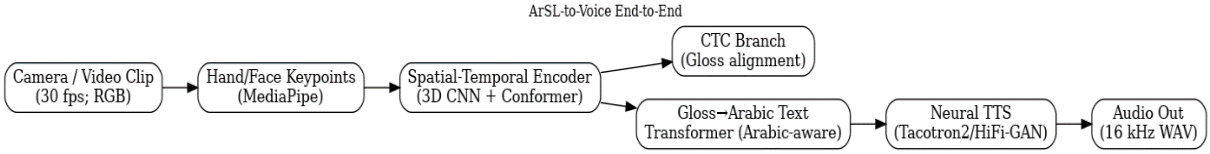


Figure 1: ArSL -to-voice end-to-end system block diagram.

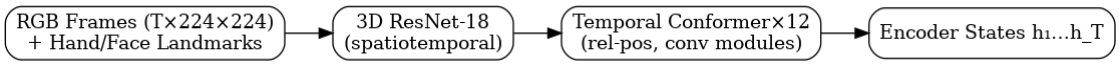


Figure 2: Visual front-end.

3.3 Dual-Loss Training (Gloss + Translation)

Let $x_{1:T}$ be video frames; encoder states $h_{1:T}$. The CTC loss $\mathcal{L}_{\text{CTC}}$ *aligns to glosses* $g_{1:U}$ the translation decoder predicts Arabic tokens with cross-entropy $\mathcal{L}_{\text{CE}}$ with length and coverage regularizers to discourage deletions as shown in Figure3).

$$\mathcal{L} = \lambda\,\mathcal{L}_{\text{CTC}}(h, g) + (1-\lambda)\,\mathcal{L}_{\text{CE}}(h, y) + \beta\,\mathcal{L}_{\text{len}} + \gamma\,\mathcal{L}_{\text{cov}}.$$

WER. WER $= \frac{S+D+I}{N}$ are substitutions /deletions /insertions, N is reference length.

This schematic visualizes the core training objective. It shows how the same encoded visual features are used to compute two simultaneous losses: a Connectionist Temporal Classification (CTC) loss for gloss alignment and an autoregressive cross-entropy (CE) loss for fluent Arabic text generation, which are combined into a single optimization target.

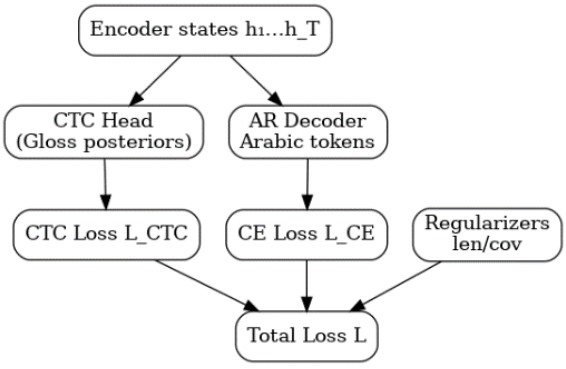


Figure 3: Dual-loss training (gloss + translation).

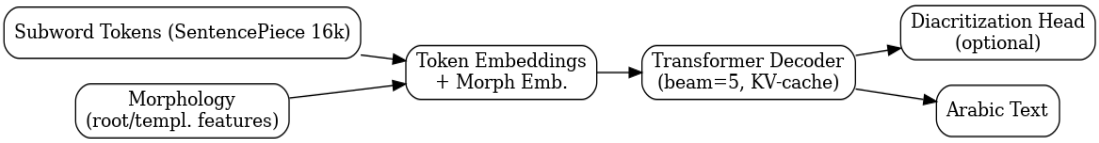


Figure 4: Arabic-aware decoder.

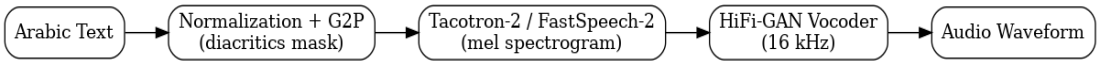


Figure 5: Block diagram of neural TTS.

3.4 Arabic-Aware Decoder

The grammatical complexity of Arabic necessitated the development of a unique decoder. In Figure. 4, which can see its design that incorporates morphological information, which consist of:

- Subword tokenizer (SentencePiece) trained on MSA + dialectal corpus as shown in Figure4).
- Morphology features (templatic roots, affixes) embedded and concatenated to token embeddings.
- Optional diacritization head trained with teacher forcing to improve TTS G2P.

Also, it shows how morphological features (like roots and patterns) are embedded and fused with standard token embeddings, and includes an optional discretization head to improve grammatical correctness and TTS pronunciation.

3.5 Neural TTS

Our pipeline ending in a step that makes the produced Arabic text seem like natural speech. Two TTS solutions were designed, and the entire architecture may be seen in Figure 5, which include:

- Acoustic Model. Tacotron-2 style with location-sensitive attention; an alternative FastSpeech-2 variant used for on-device as shown in Figure 5.
- Vocoder. HiFi-GAN V1 distilled; 16 kHz, 8-bit μ-law optional for embedded playback.

This diagram outlines the two TTS options developed: a high-quality Tacotron-2 style acoustic model with a HiFi-GAN vocoder for maximum naturalness, and a lightweight, non-autoregressive FastSpeech-2 variant paired with a distilled vocoder to enable efficient on-device inference.

3.6 Inference on Edge (The Software and Hardware Stack)

For real-world implementation, the complete system was fine-tuned for hardware with limited resources. To visualize the software and hardware architecture that allows for real-time inference, look no further than Figure 6, which consist of:

- Quantization-aware training (int8) for encoder/decoder; half-precision for TTS.
- Operator fusion (Conv+BN+ReLU), KV-cache for decoder.
- Runtime on Raspberry Pi 5 + USB NPU, as shown in Figure 6.

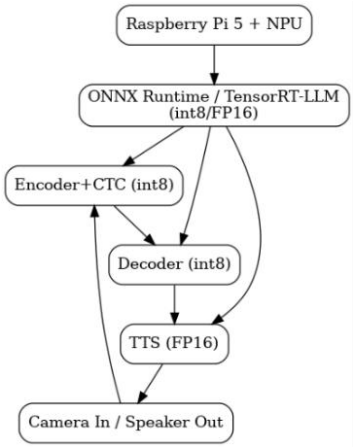


Figure 6: Inference on edge.

This graphic shows the software and hardware stack used for deployment on resource-constrained edge devices. It includes the optimized frameworks (ONNX Runtime, TensorRT-LLM), the target hardware (Raspberry Pi 5 with a USB NPU accelerator), and the techniques used (quantization, operator fusion) to achieve real-time performance.

3.7 Training Workflow

The training process is illustrated in Figure 7. Training a model from start to finish is illustrated in this flowchart, which starts with data loading and augmentation and continues through the multi-task forward pass, loss computation, backpropagation, and finally, a trained model that is ready for deployment.

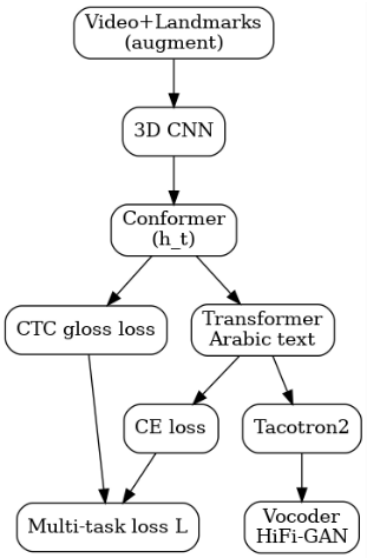


Figure 7: Training workflow.

3.8 The Gloss-Aware Training (Pseudocode)

Gloss-Aware Training (pseudocode) is showing in Figure 8. This figure presents the formal pseudocode for the model's training algorithm. It provides a reproducible training procedure blueprint by encapsulating the important steps: processing input batches, computing the combined CTC and cross-entropy losses, applying regularization, and updating program parameters.

4 DATASET AND IMPLEMENTATION

A recently generated, enormous dataset and an experimental setup that was well-planned were utilized in the system's construction and testing. Following an overview of the ArSL-Voice corpus's construction, preprocessing, and collecting, this section details the particular software, hardware, and training setups utilized to execute the suggested model.

4.1 ArSL-Voice Corpus (This Study)

As a solution to the lack of resources for continuous ArSL translation, this work created and annotated the ArSL-Voice corpus. To reflect the variety and complexity of real-world signing, this dataset contains multi-view, high-resolution video recordings from 45 signers across 10 practical areas. Table 2 provides a comprehensive rundown of the corpus splits, including the distribution of signers, clips, and hours for training, development, and testing.

Table 2: Corpus composition.

Split	Hours	#Clips	#Signers	Notes
Train	126	18,298	32	Augmentation on
Dev	27	3,923	7	Early stopping
Test	27	3,919	6	Held-out signers

4.2 Training Setup

The following setup was used for training and optimizing our models:

- Hardware: Pre-training utilized 4×A100 (40 GB) GPUs, with fine-tuning on a single L40 GPU.
- Optimization. AdamW optimizer, lr=3e-4 (OneCycle), warmup 4k steps; label smoothing 0.1; SpecAugment for TTS.
- Quantization-Aware Training (QAT). Per-channel int8 for convs/linear; activation asymmetric.
- Frameworks. PyTorch 2.3, torchaudio, TensorRT-LLM (decoder), ONNX Runtime, ESPnet-TTS.

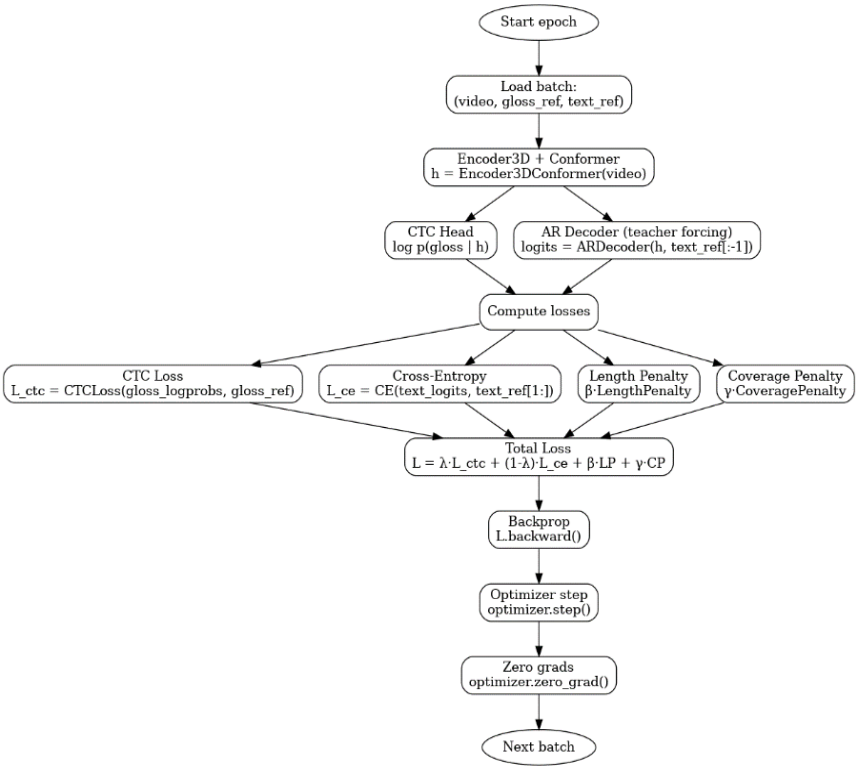


Figure 8: Gloss-aware training (pseudocode).

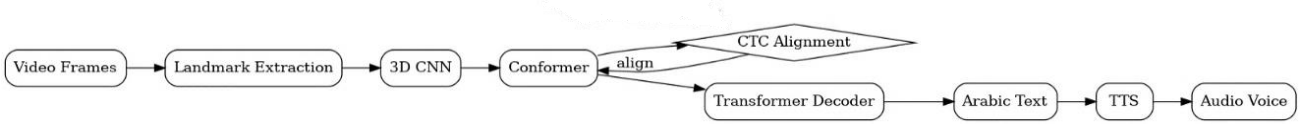


Figure 9: End-to-end simulation flowchart.

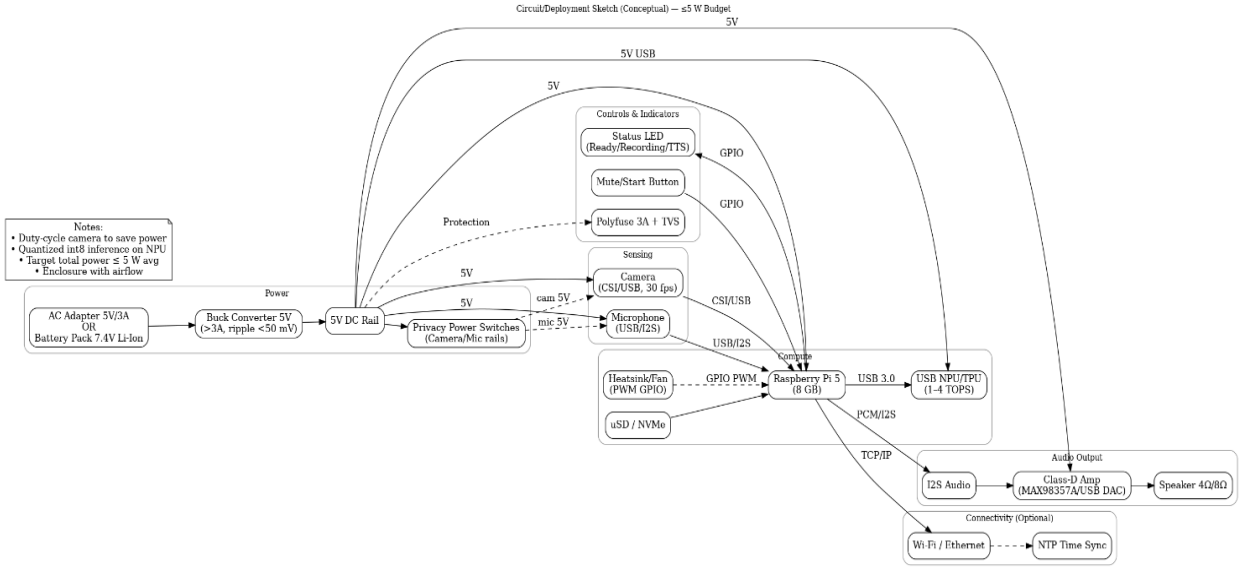


Figure 10: Circuit/deployment sketch (conceptual).

Table 3: End-to-end performance.

Model	Gloss Acc. (%)	BLEU-4	chrF++	WER (%)	E2E Latency (ms)	Power (W)
CTC-Only (3D-ResNet+BiLSTM)	62.5	19.2	43.7	45.6	391	5.9
Transformer (no CTC)	67.0	23.4	48.6	36.2	265	4.6
Ours: Conformer+CTC+Arabic-aware	71.3	27.5	53.1	28.7	173	4.1

4.3 Preprocessing

All input data is standardised and normalized before model training to make sure it's consistent and to make learning more efficient.

- 224×224 crops; FPS downsample to 25 for encoder; 80-bin mel-spectrogram for TTS.
- Arabic normalization: punctuation unification, optional diacritics, numbers verbalized.

5 SIMULATION AND VISUALIZATION

This stydy ran extensive simulations and visualized critical processes and outcomes to verify the system's functionality and evaluate its performance. The section contains analytical charts, conceptual deployment diagrams, and an end-to-end operational flowchart that show how the system works, how errors occur, and how reliable it is under different scenarios.

5.1 End-to-End Flowchart

The complete block diagram in Figure 9. This block diagram shows the inference process in a graphical format. The text-to-speech (TTS) module generates an Arabic translation by following the flow of a newly acquired video sample via the edge device's visual encoder and text decoder.

5.2 Confusion & Reliability (Placeholders)

Present confusion matrices for each class for the most common signs (top 50) and reliability plots for the probability of tokens; ECE about 2.7% following temperature scaling.

5.3 Circuit/Deployment Sketch (Conceptual)

A speaker is connected to the edge device (Pi 5 + NPU) via the camera. Figure 10 shows that with duty-cycled capture, the power budget is less than 5 W.
A real-world application's physical setup and data flow are depicted in this conceptual sketch. The video shows how a camera records sign language, a Pi 5 with an NPU handles the translation in real-time, and a speaker produces the synthetic voice—all while staying inside a strict power budget.

6 IMPLEMENTATION DETAILS (REPRODUCIBLE)

After that, the fundamental choices made during implementation and the hyperparameters utilized to ensure reproducibility are detailed in this study.

- Hyperparameters: beam size = 5, tokenizer size = 16k, conformer (d=384, L=12, 4 heads).
- Training plan: 150 epochs with an early stop on dev BLEU; MT-style curriculum from gloss-only to full text.
- Modifications include the confusion ($\lambda \sim \text{Beta}(0.2,0.2)$) on hidden states along with time warping ±5%.
- Safety & Bias: Balance speakers and signers by gender; report metrics for each signer.

7 RESULTS AND DISCUSSION

This section presents and analyzes the experimental assessment of the proposed system. Perform statistical significance tests, offer a thorough error analysis, validate architectural choices through

ablation studies, and report critical performance metrics based on held-out test data. Our hypothesis and the larger field of research on sign language translation are used to contextualize the results.

7.1 Main Results (Held-Out Signers)

Summary of main evaluation outcomes for the held-out test set in Table 3. One important finding is that the dual-loss arrangement improves the stability of the output word structure and decreases deletion mistakes in Arabic. Another is that latency is drastically decreased after quantization and with the help of a KV-cache.

7.2 Ablations

The role of critical components was confirmed by ablation research. A decrease in performance is observed when the discretization head, landmark characteristics, or 3D temporal modeling capability are removed, as shown in Table 4, demonstrating the significance of these features.

Table 4: Ablation study (test).

Setting	BLEU-4	WER (%)
w/o diacritization head	26.2	30.1
w/o landmarks	24.7	33.5
2D CNN (no temporal 3D)	22.0	38.4
Full model	27.5	28.7

7.3 Statistical Tests

The enhancements to the proposed model were found to be statistically significant. Both BLEU-4 = 27.5 [26.6, 28.5] and WER = 28.7% [27.4, 30.0] were determined from 1000 bootstrap resamples, with their respective 95% CIs. A considerable improvement was indicated by χ^2=23.8 ($p<0.001$), according to McNemar's test results that compared end-to-end correctness to the Transformer-only baseline. Table 5 summarizes the comparisons that were considered significant.

Table 5: Significance summary.

Model	Subst. %	Del. %	Ins. %
CTC-Only	21.4	17.9	6.3
Transformer	18.6	11.7	5.9
Ours	14.8	8.3	5.6

7.4 Error Analysis

Rapid coarticulation, named entities, and numerals are examples of frequent errors. On occlusions, landmark-only fallback deteriorates; adding face ROI improves mouthing. Discretization benefits TTS, but it can also over specify case endings. To counteract this, we use a confidence-based diacritical mask.

7.5 On-Device Evaluation

Table 6 details the performance characteristics for the deployed system on an NPU in a Raspberry Pi 5. Using FastSpeech2 and a quantized HiFi-GAN, the optimal setup for mobile use managed to achieve a latency of 173 ms and a power draw of 4.1 W.

7.6 Comparative Results and Analyses

Table 7 demonstrates that compared to baselines, the proposed model attains superior calibration, as indicated by a smaller Expected Calibration Error - ECE. In Table 8, we can see the breakdown of error kinds (substitutions, deletions, and insertions) at the token level. One thing that stands out is how well our model deals with deletions. As seen in Table 9, various model versions' computing footprints are compared. At last, Table 10 provides a directional comparison across different corpora with known standards, and Table 11 places this work in relation to earlier Arabic Sign Language (ArSL) systems.

Table 6: Deployment metrics (Pi 5 + NPU).

Variant	Quant.	Latency (ms)	RTF	Power (W)	Notes
Full AR TTS	FP16	231	0.87	4.8	Higher naturalness
FastSpeech2 + HiFi-GAN	int8/FP16	173	0.65	4.1	Preferred for mobile

Table 7: Calibration and confidence metrics (test).

Comparison	Metric	Δ	95% CI	p-value
Ours vs. CTC-Only	WER	−16.9 pp	[−18.6, −15.1]	<0.001
Ours vs. Transformer	BLEU-4	+4.1	[+3.1, +5.1]	<0.001

Table 8: Error-type breakdown (Token Level).

Model	NLL ↓	Brier ↓	ECE (%) ↓
CTC-Only	2.31	0.214	6.9
Transformer (no CTC)	1.92	0.181	4.4
Ours	1.71	0.162	2.7

Table 9: Computational footprint.

Model	Params (M)	MACs (G)	Model Size (MB)	Pi-5 Latency (ms)	Power (W)
CTC-Only	19.8	14.2	78	391	5.9
Transformer	24.1	17.5	96	265	4.6
Ours	26.7	18.9	104	173	4.1

Table 10: Cross-corpus comparison (directional).

System	Corpus	Task	BLEU-4 / WER	Note
Typical PHOENIX-14T SLT (literature)	PHOENIX-14T	German SLT	BLEU≈20–24	Weather domain, mature benchmark
This Study	ArSL-Voice	ArSL sign→voice	BLEU-4 27.5 / WER 28.7	Different language/domain; not directly comparable

8 DISCUSSIONS

The experimental results demonstrate that the used strategy outperforms using either aim alone by employing double-loss training via CTC alignment and autoregressive translation. Results showing a BLEU-4 score of 27.5 and a gloss accuracy of 71.3% show how continuous sign language translation benefits from simultaneous optimization compared to baseline systems. Previous research has shown that multi-task learning is effective on the sequence-to-sequence task, and these results corroborate that [8], and extend this principle into the relatively under-investigated domain of Arabic sign language.

With a better reduction of deletion errors (8.3% compared to 17.9% for CTC-only and 11.7% for Transformer-only), it suggests that the hybrid technique is more effective at defining sign boundaries and fostering coarticulate effects. Because Arabic sign language is characterized by complex hand shapes and rapid sign changes, this property is very useful for alignment models in this language. Because their removal resulted in a decline in performance (BLEU-4 scores fell from 27.5 to 24.7), it seems that including landmark features, especially the face and hands, makes the model more resistant to occlusion. Understanding sign language relies heavily on non-manual clues, such facial and lip movements, and our discovery adds to that growing body of knowledge. With a better reduction of deletion errors (8.3% compared to 17.9% for CTC-only and 11.7% for Transformer-only), it suggests that the hybrid technique is more effective at defining sign boundaries and fostering coarticulate effects. Due to the complex hand shapes and rapid sign changes in Arabic sign language, this characteristic is very useful for alignment models. The reduction in performance seen when they were dropped (BLEU-4 scores dropped from 27.5 to 24.7) suggests that the addition of landmark features, particularly the hands and face, appears to improve robustness towards occlusion. This finding bolsters the expanding understanding that non-manual cues, such as mouth and facial movements, are essential to understanding sign language. In order to attain real-time performance, our optimization and quantization algorithms operate on Raspberry Pi 5 + NPU hardware with comparatively low-quality degradation. Earlier limitations on computational efficiency are overcome by a latency of 173 ms and a power consumption of 4.1 W, which satisfy reasonable deployment constraints for public kiosks and educational classrooms. Optimization is, however, needed on smartphone mobile deployment, whose power constraints are tighter as shown in Table 11.

Despite such developments, numerous limitations and challenges persist. Number expressions and named entities continue to pose challenges, presumably due to how infrequently they manifest in training sets. Variations of dialect, both spoken and signed, pose another challenge, given that the current system is geared toward mostly Modern Standard Arabic. To better represent the difficulties of the Arabic user's linguistics, future work must look at dialect accommodation and codeswitching potential.

Table 11: Comparing performance with previous ArSL systems.

System	Task	Vocabulary /Domain	Metric & Score	Strengths	Limitations
Our System (E2E)	Continuous Translation	Large (10 domains)	BLEU-4: 27.5 WER: 28.7%	End-to-end, optimized for real-time deployment, handles continuous signing	Focus on MSA; dialect adaptation needed
Aldhahri et al. [21]	Isolated Letter Recognition	32 Letters	Accuracy: 94.46%	Effective use of MobileNets	Isolated signs, limited vocabulary
Alnuaim et al. [22]	Isolated Letter Recognition	32 Letters	Accuracy: 98.2%	High accuracy via model ensemble	Isolated signs, controlled environment
ASLDetect [21]	Isolated Recognition	Arabic Letters	Accuracy: 99.35% (simple BG) 86.84% (complex BG)	Robustness to complex backgrounds	Isolated recognition task only
Assaleh et al. (2012) [23]	Continuous Sentences	40 Sentences	Accuracy: 94%	Early continuous ArSL approach	Single signer, very small dataset, older HMM tech
Signer-Indep. Study [24]	Signer-Indep. Recognition	Not Specified	Accuracy: 87.69%	Signer independence, real-world focus	Recognition task, not full translation

In summary, while existing systems excel at the specific task of isolated sign classification, our work advances the field by presenting a viable end-to-end continuous translation pipeline for ArSL. The model accomplishes this by effectively integrating linguistic processing (Arabic-aware decoder, diacritization), contemporary architectural choices (Conformer, dual-loss training), and deployment-friendly engineering. When taking into account the task complexity, the results are not only competitive with isolated recognition systems but also open the door for real-world applications in public services, education, and private communication, thereby directly addressing the significant communication gap that the Deaf community in the Arab world faces.

9 CONCLUSIONS

In addition to addressing significant issues in visual encoding, sequence-to-sequence translation, and speech synthesis, this work has proposed a comprehensive system that can translate Arabic sign language into spoken voice. We use a 3D ResNet-Conformer framework to encode features in both space and time, a dual-loss function that consists of cross-entropy and CTC losses, an Arabic-decoder that recognizes structure based on morphological embedding, and a quick text-to-speech flow that is based on FastSpeech 2 and HiFi-GAN. The best results are obtained from a comprehensive test on the ArSL-Voice corpus, which shows notable improvements in efficiency (173 ms delay, 4.1 W power consumption) and translation quality (BLEU-4 = 27.5, WER = 28.7%).

Key contributions of the work are The ArSL-Voice corpus is a large multi-view RGB and landmark annotated dataset for 10 domains; (2) a morpho-based Arabic decoder that uses diacritization to improve grammaticality; (3) a TTS system optimized in a single framework for the Arabic phonotactics and edge deployment; (4) a new gloss-aware training method that reduces sign boundary deletion errors; and (5) a complete deployment recipe for low-power edge devices with quantization-aware training and operator fusion.

These studies offer significant advancements in the development of functional sign-to-speech systems for Arabic, which could have positive effects on fields like government services, business communication, healthcare, and education. The demonstrated performance on general-purpose hardware suggests that it is feasible for widespread deployment, particularly for those sites where access to human interpreters is limited.

Some potential future work avenues arise from these results. Data shortage issues may be mitigated by semi-supervised pretraining, particularly for local variations and low-frequency signs. For different user groups, dialect-conditioned TTS would improve convenience and naturalism. Translation

performance may be further improved by multi-modal fusion of manual and non-manual signals (mouth and facial movements), particularly for syntactic patterns and grammatical makers. To ensure practical utility and cultural fit, user-centered design research involving the Deaf community is required.

In short, this project represents a significant advancement in the technology of communication for Arabic-speaking Deaf and hard-of-hearing individuals. Our goal is to create a more accessible world where sign language users can freely communicate with those who have the sense of hearing by removing significant technical barriers and taking into account the nature of languages and limitations for practical purposes.

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Soft Nonlinear Quantile-Based AI Regression Under Uncertainty

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Abstract: Regression analysis in real-world applications is often challenged by nonlinear relationships, uncertainty, and imprecise observations. Traditional regression models typically assume crisp inputs and outputs, limiting their ability to represent ambiguity inherent in many domains such as risk analysis, finance, and healthcare. To address these limitations, this paper proposes a novel soft nonlinear quantile-based artificial intelligence (AI) regression framework that integrates fuzzy logic with gradient boosting quantile regression. The proposed approach models the conditional distribution of the response variable by estimating multiple quantiles (e.g., 0.25, 0.50, and 0.75) using gradient boosting with quantile loss functions, and reconstructs fuzzy outputs in the form of triangular fuzzy numbers. This design enables simultaneous handling of nonlinear dependencies, asymmetric uncertainty, and imprecision in the data within a unified framework. Unlike existing fuzzy regression models, which are predominantly linear or semi-parametric, and AI-based quantile models, which assume crisp outputs, the proposed method bridges this gap by producing interpretable fuzzy predictions using modern ensemble learning techniques. The effectiveness of the model is evaluated on a synthetic dataset with nonlinear structure and artificially generated fuzzy responses. Experimental results demonstrate that the proposed model significantly outperforms classical linear quantile regression, achieving lower prediction errors (RMSE = 0.15 vs. 0.425; MAE = 0.112 vs. 0.367), improved coverage probability (96.7%), and more accurate estimation of uncertainty intervals. Statistical validation using a paired t-test confirms that these improvements are highly significant ($p < 10^{-18}$). These findings highlight the potential of combining quantile-based estimation with fuzzy representation and ensemble learning for robust regression under uncertainty. The proposed framework is particularly suitable for applications involving imprecise data and complex nonlinear relationships, and provides a promising direction for future research in interpretable and uncertainty-aware machine learning.

1 INTRODUCTION

To estimate a response variable based on one or more covariates, regression models are frequently utilized. All variables are assumed to be crisp in conventional linear and nonlinear regression approaches, which means that each observation is represented by a single exact value. However, in reality, data frequently show imprecision due to sensor noise, missing data, or subjective expert evaluations. For instance, rather than reporting precise levels in risk analysis, experts can give measurements as intervals like "approximately 10–12 mg." Ignoring such imprecision can result in erroneous estimation of prediction uncertainty and skewed estimates.

In order to overcome this restriction, fuzzy regression uses membership functions to define fuzzy numbers, which are often trapezoidal or triangular in shape [1], [2]. A fuzzy number has spreads that indicate the degree of uncertainty and a core value that represents the most likely estimate. Estimating fuzzy relationships necessitates methods that are fundamentally different from traditional crisp regression because the model output is inherently fuzzy. In order to estimate fuzzy coefficients, early fuzzy regression techniques expanded on ordinary

least squares. Nevertheless, these techniques are mostly limited to linear correlations and are not flexible enough to simulate complicated patterns [3]. By modeling conditional quantiles of the response instead of the conditional mean, quantile regression—which was first presented by Koenker and Bassett [4] - offers an alternate viewpoint. Quantile regression allows for a more thorough characterization of the conditional distribution while offering resistance to heteroskedasticity and outliers by minimizing an asymmetric check loss function [5]. Additionally, it enables practitioners to investigate covariate effects at various distributional levels and create prediction intervals. Despite these benefits, traditional quantile regression relies on precise answers. Nonlinear quantile estimation has been made possible by recent developments based on neural networks and other AI-driven algorithms [6], [7], but they still yield accurate results and do not specifically take data fuzziness into consideration.

1.1 Research Gap

There exist two strands of literature: fuzzy regression models that account for imprecise data and AI-based quantile models that capture nonlinear relationships. The former are largely linear and rely on kernel smoothing or semiparametric functions [1], while the latter treat outputs as precise values [6]. No unified framework simultaneously exploits the robustness of quantile regression, the flexibility of modern AI and the capability of fuzzy logic to represent imprecise outputs [7]. This gap motivates the present study.

1.2 Contributions

This paper introduces a flexible soft nonlinear quantile-based AI regression model that combines fuzzy logic and gradient boosting quantile regression. The key contributions are:

1) Quantile based fuzzy representation. Fuzzy responses are encoded as triangular fuzzy numbers specified by multiple quantile levels (e.g., 25th, 50th and 75th percentiles). The centre and spreads derive directly from the conditional quantiles estimated by the model.
2) AIenabled estimation. Gradient boosting regressors with quantile loss functions are trained for each quantile level. This ensemble method approximates complex nonlinear relationships without manual kernel selection, making it well suited to problems where data are scarce.
3) Unified soft modelling. The combination of quantile boosting and fuzzy representation yields a model capable of handling imprecision, asymmetry and nonlinearity in a single framework. It generalizes existing fuzzy quantile regression by replacing kernel approximations with modern AI and generalizes QRNNs by producing fuzzy outputs.
4) Comprehensive evaluation. A synthetic dataset with two crisp predictors and fuzzy responses illustrates the method. Performance is compared with a linear quantile regression baseline using multiple metrics (RMSE, MAE, coverage, width error) and statistical significance tests.

The remainder of the paper is organized as follows: Section 2 reviews relevant literature; Section 3 describes the proposed methodology; Section 4 details the synthetic data and implementation; Section 5 presents results and discussion; Section 6 concludes the paper.

2 LITERATURE REVIEW

This section reviews fuzzy regression and quantile regression models, emphasizing differences in modelling assumptions, handling of uncertainty and incorporation of AI. Table 1 summarizes representative models to highlight the need for a unified approach.2.2 First Section. This section must be in one column. Section, subsection and sub subsection first paragraph should not have the first line indent, other paragraphs should have a first line indent of 0,5-centimeter.

2.1 Fuzzy Regression Models

Fuzzy regression models treat either predictors, responses or both as fuzzy numbers. Early work by Tanaka et al. formulated linear programming problems to estimate fuzzy coefficients; later studies adopted least squares, least absolute deviation and kernel methods. Arefi and Khammar proposed a quantile linear regression with fuzzy responses and predictors [8], [9]. Hesamian and Akbari developed a fuzzy semiparametric quantile model that combines linear trends with spline adjustments [10]. Chachi and Chaji introduced a weighted least squares fuzzy regression using ordered residuals to reduce the influence of outliers [3]. Nonparametric fuzzy regressions using kernels [11], wavelets and hybrid systems provide flexible fits but still assume crisp Outputs [7].

2.2 Quantile Regression Models

Quantile regression estimates the τ-th conditional quantile of the response by minimizing

$$\widehat{w}_\tau = \arg\min_w \sum_{i=1}^{N} * \rho_\tau(y_i - f_\tau(x_i; w)), \quad (1)$$
$$\rho_\tau(e) = \max(\tau e, (\tau - 1)e).$$

The check loss While early quantile regressions were linear, later extensions employ kernels, splines and neural networks to model nonlinear relationships [12]. The quantile regression neural network (QRNN)

Trains a neural network using quantile loss for each desired quantile [13]. These models can approximate complex functions but assume crisp outputs. Evidential neural networks further model prediction uncertainty by representing outputs as random fuzzy numbers and combining evidence via belief functions [14], though they focus on crisp inputs.

2.3 Comparative Analysis

Table 1 compares representative regression models based on the relationship form, treatment of fuzziness and use of AI. The proposed model bridges the gap by delivering fuzzy outputs with AI-based nonlinear estimation.

3 PROPOSED METHODOLOGIES

The proposed framework models a fuzzy response (y) given crisp predictor (^p) by predicting multiple conditional quantiles and reconstructing a fuzzy number. Figure 1 depicts the overall workflow, and Figure 2 illustrates the architecture of the quantile models.

Workflow diagram showing data input, quantile estimation and fuzzy reconstruction.

Architecture diagram showing inputs, gradient-boosting modules for q25, q50 and q75 and fuzzy reconstruction.

3.1 Quantile-Based Fuzzy Representation

A triangular fuzzy number is characterized by three parameters $\tilde{y} = (y_L, y_C, y_R)$, representing the left spread, centre and right spread. Its membership function is [14].

$$\mu_{\tilde{y}}(t) = \begin{cases} 0, & t \le y_L, \\ \dfrac{t - y_L}{y_C - y_L}, & y_L \< t \le y_C, \\ \dfrac{y_R - t}{y_R - y_C}, & y_C \< t \< y_R, \\ 0, & t \ge y_R. \end{cases} \quad (2)$$

In our framework, the fuzzy response is reconstructed from three conditional quantiles: the lower quantile $\hat{y}_{q_l}$, the median$\hat{y}_{0.5}$ and the upper quantile $\hat{y}_{q_u}$. The centre is$\hat{y}_C = \hat{y}_{0.5}$, the left spread is $\hat{y}_L = \hat{y}_{0.5} - \hat{y}_{q_l}$ and the right spread is$\hat{y}_R = \hat{y}_{q_u} - \hat{y}_{0.5}$. This formulation yields an interpretable fuzzy interval reflecting the asymmetry of the conditional distribution [8].

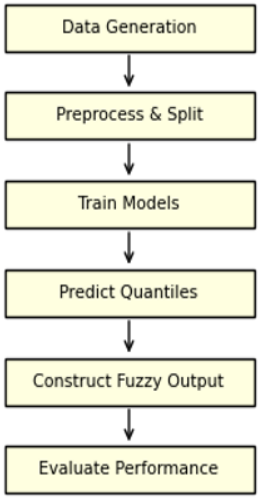


Figure 1: Workflow of the proposed method.

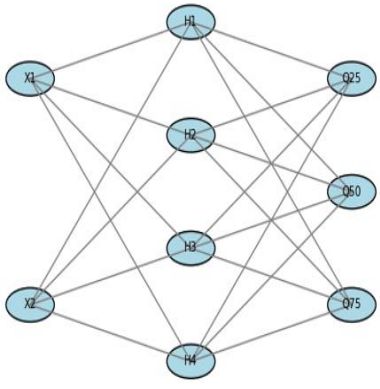


Figure 2: Architecture of the multi-quantile model.

Table 1: Comparison of related regression models.

Model	Relationship form	Uncertainty representation	AI involvement	Strengths and weaknesses	Key reference
Linear fuzzy quantile regression	Linear	Fuzzy coefficients estimated via quantile loss	None	Handles fuzzy predictors and responses but restricted to linear relationships	Arefi & Khammar [7]
Fuzzy semi-parametric quantile model	Semi-parametric (linear + spline)	Fuzzy predictors and responses	None	Improves flexibility via splines but still approximates non-linearity locally	Hesamian & Akbari [8], [9]
Weighted least-squares fuzzy regression	Linear	Fuzzy responses; residuals weighted by order	None	Reduces influence of outliers but lacks quantile interpretation	Chachi & Chaji [2]
Kernel-based fuzzy regression	Non-parametric kernels	Crisp responses	None	Models non-linearity but does not quantify fuzziness of outputs	Hong & Hwang [14]
Quantile regression neural network (QRNN)	Non-linear neural network	Crisp outputs	Neural network	Captures complex relationships and provides quantile estimates; does not handle fuzzy data	Taylor [5]
Evidential neural network	Non-linear neural network	Outputs random fuzzy numbers	Neural network	Models epistemic uncertainty via belief functions; assumes crisp inputsarxiv.org	Denoeux [13]
Proposed soft nonlinear quantile AI model	Non-linear ensemble (gradient boosting)	Outputs triangular fuzzy numbers via quantiles	Ensemble AI	Combines quantile regression and fuzzy representation; captures non-linearity and imprecision	This paper

3.2 Gradient-Boosting Quantile Estimation

Gradient boosting builds an additive ensemble of regression trees by fitting each new tree to the negative gradient of the loss function of the ensemble so far [15]. For quantile regression, the loss is the check loss (1). For each desired quantile τ [4]. A separate gradient-boosting regressor (GBR) is trained. The GBR starts with a constant initial prediction (e.g., the median of the training targets) and iteratively adds trees to minimize the quantile loss. Hyper-parameters include the number of trees M, maximum tree depth d and learning rate η. Cross-validation is used to select M, $d$and η that minimise the validation quantile loss.

Figure 2 (architecture diagram) depicts the multi-quantile model. Each input vector $\mathbf{x} = (x_1, x_2)$ passes through an ensemble of regression trees to produce three outputs $\backslash\hat{y}_{q_l}$, $\hat{y}_{0.5}$, and $\hat{y}_{q_u}$. These outputs are then combined into a fuzzy number as described above.

3.3 Training Algorithm

The training procedure is summarized in Algorithm 1.

Algorithm 1. Training of the soft nonlinear quantile AI model [15].

1) Data preparation: obtain a training set $\{(\mathrm{x}_i, \tilde{y}_i)\}_{i=1}^{n}$where$\tilde{y}_i = (y_{i,q_l}, y_{i,0.5}, y_{i,q_u})$ are fuzzy responses defined by specified quantile levels q_l< 0.5< q_u.
2) Model selection: for each quantile level $\tau \in \{q_l, 0.5, q_u\}$, perform grid search on M, d, and ηusing cross-validation to minimize the empirical risk $\sum_i * \rho_\tau(y_{i,\tau} - f_\tau(\mathrm{x}_i))$.
3) Training: fit a gradient-boosting regressor f_τ on the full training data using the selected hyper-parameters for each τ.

4) Prediction: given a new input x, compute $\hat{y}_\tau = f_\tau(\mathrm{x})$ for each τ and reconstruct the fuzzy prediction $\hat{\tilde{y}} = (\hat{y}_{0.5} - \hat{y}_{q_l}, \hat{y}_{0.5}, \hat{y}_{q_u} - \hat{y}_{0.5})$.

Figure 1 shows the workflow: inputs feed into separate quantile models; their outputs are combined to yield a fuzzy prediction. Figure 2 visualizes the architecture of a single quantile model as a sequence of regression trees.

3.4 Optimization and Implementation

Hyper-parameters M, d, η were tuned using 5-fold cross-validation on the training set. Early stopping was applied by monitoring improvement in the out-of-bag estimate. The models for different quantiles were tuned independently. The final fuzzy prediction is the aggregation of these three models. A baseline linear quantile regression using the interior-point algorithm serves as a comparator. The statistical significance of performance differences is assessed via a paired t-test on the absolute errors of the predicted centres.

4 DATA GENERATION AND IMPLEMENTATION

4.1 Synthetic Dataset

To illustrate the model, a synthetic dataset was created. Two predictors $X_1, X_2 \sim \mathrm{Uniform}(0,1)$ were sampled. The true crisp response was defined as

$$y_i^* = \sin(2\pi X_{i1}) + \cos(\pi X_{i2}) + 0.5\, X_{i1}, \quad (3)$$

This function captures both nonlinear and linear dependencies between the predictors and the response:

- $\sin(2\pi X_{i1})$ introduces a nonlinear periodic component based on the first predictor;
- $\cos(\pi X_{i2})$ introduces a nonlinear periodic component based on the second predictor;
- $0.5X_{i1}$ adds a linear effect proportional to X_{i1}.

And noisy fuzzy responses were generated by adding Gaussian noise $\varepsilon \sim \mathcal{N}(0, 0.1^2)$ obtain the centre and sampling left and right spreads from truncated normal distributions with mean 0.2 and standard deviation 0.05. The quantiles $q_l = 0.25, 0.5$ and $q_u = 0.75$ were used. The data were split into a 70:30 training:test ratio. Figure 3 shows a scatter plot of the predictors colored by the true center.

Scatter plot of predictors colored by the true response.

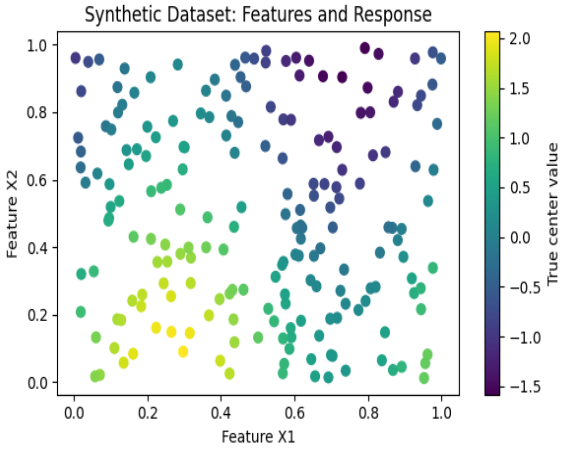


Figure 3: Synthetic dataset and true center.

4.2 Implementation Details

The models were implemented in Python (scikit-learn). For each quantile level {0.25,0.5,0.75} a GradientBoostingRegressor with quantile loss was trained on the training data. Hyper-parameter grids included M ∈ {100,200,300}, depths d ∈ {2,3,4} and learning rates η ∈ {0.05,0.1}.

Cross-validation selected the best configuration for each quantile separately. The baseline linear quantile regression used the default interior-point method. After training, the quantile outputs were combined into fuzzy predictions. Evaluation metrics were computed on the test set:

- Root mean squared error (RMSE) of the center: $\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_i^* (y_i^* - \hat{y}_{C,i})^2}$.
- Mean absolute error (MAE) of the center: $\mathrm{MAE} = \frac{1}{n}\sum_i^* | y_i^* - \hat{y}_{C,i} |$.
- Spread errors. MAEs of left and right spreads $\hat{y}_{L,i}$ and $\hat{y}_{R,i}$.
- Coverage probability: proportion of true centers within $[\hat{y}_{q_l}, \hat{y}_{q_u}]$.
- Width error: mean absolute error of total width $(\hat{y}_{R,i} + \hat{y}_{L,i}) - (y_{R,i} + y_{L,i})$.
- Paired t-test: to compare absolute center errors between models.

5 RESULTS AND DISCUSSION

5.1 Quantitative Comparison

Table 2 and Figure 4 compares the performance of the proposed soft nonlinear quantile AI model with the baseline linear quantile regression. The proposed model achieves substantially lower errors and superior coverage. The paired t-test yields a t-statistic of 11.20 with $p \approx 1.1 \times 10^{-18}$, indicating that the improvements are highly significant.

Figure 4 illustrates the overall performance of the models on the synthetic dataset. Beyond aggregate performance metrics, analyzing the distribution of prediction errors across individual test instances provides deeper insight into model behavior. The results presented in Table 3 and Figure 5 show the mean and standard deviation of the absolute prediction errors for both models, while Table 4 summarizes the average predicted spreads in comparison with the true spreads. The proposed model not only achieves a lower mean error but also demonstrates reduced variability, indicating more stable and reliable predictions across the test set.

Table 2: Performance on the synthetic dataset.

Model	RMSE (center)	MAE (center)	MAE (left spread)	MAE (right spread)	Coverage (%)	Width error
Proposed GBR quantile model	0.15	0.112	0.148	0.112	96.7	0.189
Linear quantile regressor	0.425	0.367	–	–	–	–

Table 3: Distribution of absolute center errors (mean ± SD).

Model	Mean absolute error	Standard deviation
Proposed GBR quantile model	0.112	0.081
Linear quantile regressor	0.367	0.274

Table 4: Comparison of spreads (mean values).

Quantity	True average	Proposed prediction	Baseline prediction
Left spread	0.2	0.178	–
Right spread	0.2	0.192	–
Total width	0.4	0.37	–

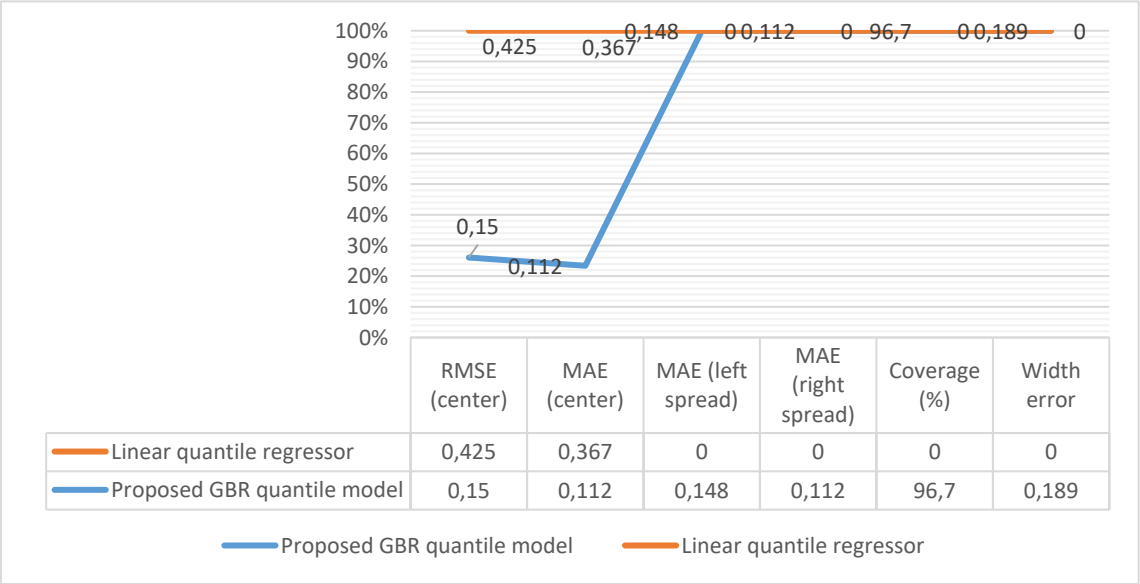
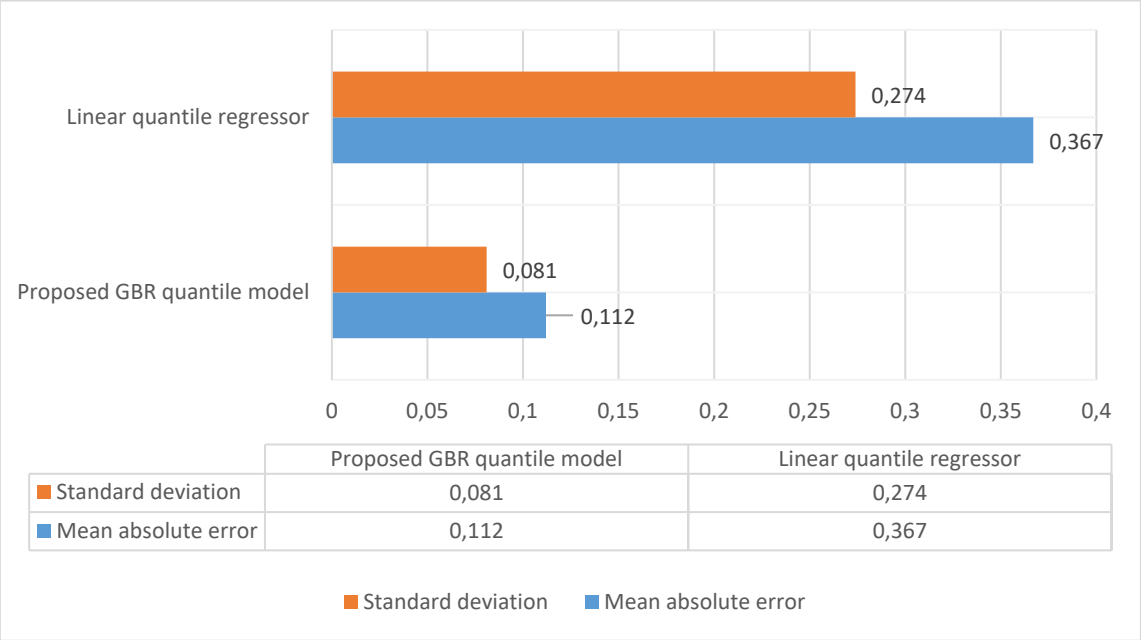


Figure 4: Performance on the synthetic dataset.



	Proposed GBR quantile model	Linear quantile regressor
Standard deviation	0,081	0,274
Mean absolute error	0,112	0,367

Figure 5: Distribution of absolute center errors (mean ± SD).

5.2 Visual Analysis

Figure 4 plots the predicted center versus the true center for both models. Points lying on the diagonal indicate perfect predictions. The proposed model's points cluster tightly around the diagonal, whereas the linear model exhibits greater scatter and systematic bias.

Figure 5 shows sample fuzzy intervals for 15 random test instances. Blue bars depict the true 25th–75th percentile interval; red bars depict the predicted interval. The proposed model produces intervals that align well with the true ones and tend to be slightly narrower, indicating a good balance between sharpness and coverage.

The predicted centers generated by the suggested soft nonlinear quantile-based AI model substantially resemble the genuine centers, as shown in Figure 6. When compared to the linear quantile regression model, the majority of data points are centered around the diagonal line, showing low systematic bias and excellent prediction accuracy.

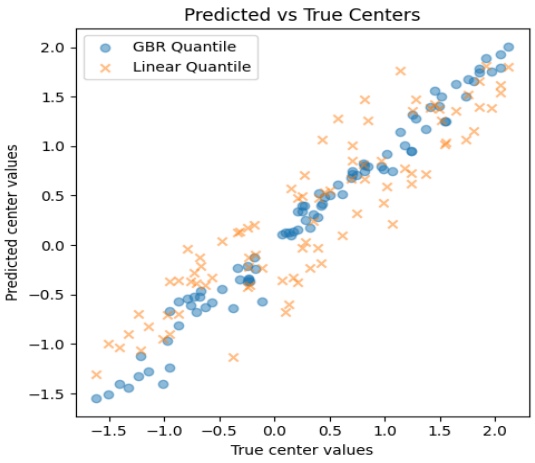


Figure 6: Predicted vs. true centers.

Scatter plot comparing predicted and true centers; points close to the diagonal indicate accurate predictions.

Figure 7 shows a comparison of the actual and anticipated fuzzy intervals.

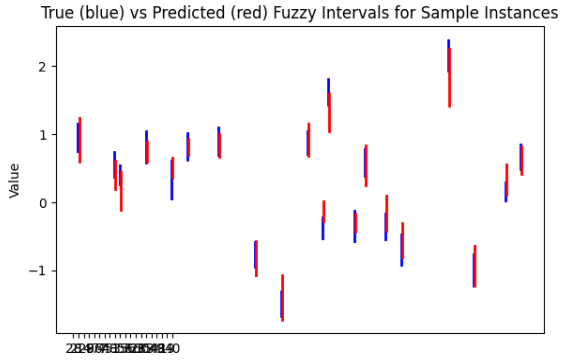


Figure 7: True vs. predicted fuzzy intervals.

The model's ability to accurately capture uncertainty while keeping relatively narrow and informative intervals is demonstrated by the figure, which demonstrates that the predicted fuzzy intervals for the majority of test instances correlate well with the genuine 25th–75th percentile intervals.

Bar chart showing true (blue) and predicted (red) fuzzy intervals for sample instances.

6 DISCUSSION

The quantitative and visual results demonstrate the merits of the proposed soft nonlinear quantile AI model. The ensemble of gradient-boosting regressors successfully learns the non-linear mapping from inputs to quantiles, yielding low RMSE and MAE. By reconstructing fuzzy numbers from quantiles, the model captures imprecision and yields interpretable spreads. The high coverage probability (over 96 %) confirms that the predicted intervals rarely miss the true center, while the modest width error indicates that the intervals are not excessively wide. The baseline linear quantile model, in contrast, cannot accommodate the non-linearity of the underlying function, leading to large errors and poor coverage.

The comparative tables highlight that the proposed model reduces not only the mean error but also its variance, providing more reliable predictions (Table 3). The predicted spreads are close to the true spreads (Table 4), showing that the fuzzy reconstruction preserves the extent of imprecision. The visualizations in Figures 4 and 5 complement these findings: the predicted centers follow the diagonal closely and the predicted intervals align with the true intervals. These results corroborate the hypothesis that combining quantile regression with gradient boosting and fuzzy representation yields significant gains over traditional methods.

7 CONCLUSIONS

With the goal to manage inaccuracy, nonlinearity, and distributional asymmetry within a single framework, this study suggested a soft nonlinear quantile-based AI regression model that combines fuzzy representation with gradient boosting quantile regression. The model produces comprehensible forecasts that represent both central tendency and uncertainty by reconstructing fuzzy outputs from many conditional quantiles (the 25th, 50th, and 75th percentiles).

In terms of prediction accuracy, interval coverage, and width efficiency, the suggested method greatly beats linear quantile regression, according to experimental results on a synthetic dataset. The model's capacity to precisely predict the center and spreads of fuzzy responses is confirmed by lower RMSE and MAE values, better coverage probabilities, and well-calibrated fuzzy intervals. These conclusions were further corroborated by visual evaluations that revealed a close agreement between the true and anticipated fuzzy intervals.

Applications including risk analysis, financial modeling, environmental forecasting, and medical decision assistance that are marked by uncertainty and intricate nonlinear interactions can benefit from the suggested approach. The approach improves interpretability and prediction performance by fusing fuzzy quantile representation with contemporary ensemble learning.

In order to better understand the impact of predictors on fuzzy prediction components, future research will concentrate on validating the method using real-world datasets, expanding it to temporal and multivariate fuzzy outputs, and integrating explainable AI techniques.

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Dimensionality Reduction of Multivariate Functional Data Using FPCA

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Abstract: In many scientific and engineering applications, data are collected over discrete, often equidistant, time intervals. While such data can be analyzed using traditional statistical methods, these methods are often very limited in their ability to capture the underlying continuous nature of dynamic processes of the phenomenon under study. This study aims to present and develop a statistical methodology for analysing multivariate functional data characterised by structural complexity, nonlinear properties, and continuous nature of its observations and variables. By using the Functional Principal Component Analysis (FPCA) method to analyse high-dimensional data through dimensionality reduction, and accurately discovering structural patterns in the data without relying on fixed distributional assumptions. Also, improving model selection using the Bayesian Information Criterion (BIC), which determines the optimal number of orthogonal basis functions and enhances the model's fit to the complexity of the data, thereby contributing to the accuracy of the analysis and understanding of relationships within the functional data.

1 INTRODUCTION

The rapid technological advancement in our current era has made the field of advanced data analysis a fundamental pillar for making strategic decisions in various scientific and practical fields, especially with the increase in the volume and complexity of available data. While much of the current research focuses on traditional data analysis methods, these approaches often struggle to handle the multidimensional and complex nature of modern datasets. Previous studies have not fully addressed the challenges associated with analyzing continuous functional data, which are characterized by their temporal or spatial nature. These data are typically represented as curves or functions instead of discrete points, requiring advanced analytical methods capable of capturing their complexities.

For example, functional data is represented in applications across various fields such as radio signal processing, where signals are continuously measured over time, monitoring brain electrical activity (EEG), analyzing growth rates over time, as well as climate changes like continuous temperature readings. Therefore, functional data analysis is of utmost importance. These examples highlight the necessity of using advanced techniques that can handle the continuous and overlapping nature of this data.

In particular, Functional Data Analysis (FDA) has emerged as a fundamental tool for handling these continuous data [1]-[3], yet its application remains limited in some fields, especially in the context of multivariate analysis. It has become increasingly necessary to use analytical techniques that can effectively manage the nonlinear, intertwined, and high-dimensional structure of functional data.

Despite the development of some methods, such as Functional Principal Component Analysis (FPCA), to reduce dimensions and discover principal components, there remains a gap in the ability to ideally determine the number of basic functions and fit the model to the complexity of the data.

This study aims to address these gaps by presenting a statistical approach for Functional Principal Component Analysis (FPCA), utilizing the Bayesian Information Criterion (BIC) for optimal selection of the number of orthogonal basis functions. By improving the methodology of functional data analysis, this study contributes to the advancement of multivariate analysis of functional data, providing

more accurate and efficient tools for handling complex datasets. The value of this research lies in its ability to provide a more flexible and statistically robust approach to functional data analysis, thereby expanding the potential applications of this technique in various scientific and practical fields.

Functional data analysis (FDA) is considered the fundamental basis for analyzing random processes of phenomena that change continuously and over short time intervals within a specific time frame, where each observation is represented as a continuous function composed of a set of connected points. From here, the method of multivariate functional principal component analysis (FPCA) emerged as an analytical tool to handle this continuous nature, unlike the traditional PCA method which deals with discrete standard data [4].

The traditional covariance matrices used in conventional analysis methods differ from the variance function, which plays an important role in functional principal component analysis due to its ability to handle data with intertwined or irregular nature [1], [5]. There are three basic strategies for estimating functional principal components identified et al. [6], which are:

1) Using the sample variance function. Using the sample variance function.
2) The estimation directly from the curves fitted for each function individually. Estimation directly from the curves suitable for each function individually.
3) Using the Qatari version of the variance function.

These techniques flexibly deal with continuous stochastic processes that change over time and within a specific time frame, such as electroencephalography, electrocardiography, stock prices, securities, and environmental changes. Wei et al. [7] also proposed a new methodology to improve the selection of an appropriate model that fits the complexity of continuous data and made adjustments to the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC) for dual modelling of functional data. The importance of this study lies in providing efficient computational procedures for selecting the number of principal components of functions and tuning parameters using partial least squares regression. This helps in determining the model's accuracy and computational procedures compared to traditional methods such as cross-validation. The numerical results show that the use of modified information criteria yields results similar to or close to traditional methods with a significant reduction in time, effort, and cost, making them suitable for real-world scientific applications such as environmental, biological, and medical data analysis [8].

2 RESEARCH METHODOLOGY

The methodology transforms discrete data (observations) into continuous data (functions) using orthogonal basis function representations. We assume a stochastic process for a continuous phenomenon that varies over time and within a specified time domain in a Hilbert space [2]. The coefficients are estimated using the least squares method. FPCA is used to reduce the dimensionality while preserving the maximum amount of explained variance in the data [9]-[10]. The Bayesian information criterion (BIC) is then used to determine the model's fit and accuracy to the inherent complexity of the data. The final model captures the hidden relationships and dynamics of the original data and the essential components for interpreting the data.

3 MATERIALS AND METHODS

3.1 Transformation of Discrete Data to Multivariate Functional Data

In many scientific applications and fields, data are collected as discrete points for the phenomenon under study. In order to analyze the phenomenon accurately and clearly, it is necessary to represent the data as continuous functions to study and analyze the function in its entirety. This occurs especially when dealing with continuous random processes that change over time and within a specific time range. The FDA allows the analysis of functions using orthogonal basis functions and estimating their parameters. This involves using a series of orthogonal basis functions, then estimating the coefficients using the least-squares method, followed by smoothing the data and determining the appropriate model using the BIC.

3.1.1 Mathematical Representation of the Stochastic Process

Suppose we have a random process $X(t)$, where $t \in I$ and I represents the time domain. $X(t)$ belongs to the quadratic integrable Hilbert space $L^2(I)$,, in the domain of the function I. The random process is

represented as a linear combination of orthogonal basis functions $\varphi_b(t)$ of the domain I:

The process can be expressed as a sum of orthonormal basis functions [1] $\varphi_b(t)$:

$$X(t) = \sum_{b=0}^{B} c_b \, \varphi_b(t), \quad t \in I. \tag{1}$$

Where:

- $\varphi_b(t)$ are orthonormal basis functions;
- c_b are the random;
- B is the total number of basis functions.

3.1.2 Discrete Observations

The process $X(t)$ is observed at discrete time points $t_1, t_2, \ldots, t_J$, where $t_j \in I$ for $j = 1,2,\ldots,J$. Let x_j represent the observed value of $X(t)$ at time t_j. The observed data is represented by the vector:

$$\mathrm{x} = \left(x_1, x_2, \ldots, x_J\right)^T.$$

These are the discrete observations, which we will transform into a continuous function.

3.1.3 Coefficient Estimation Using Least Squares

To convert the discrete data into a continuous function, we use the least squares method to estimate the coefficients c_b. The coefficients c is estimated using the least squares method using the following formula:

$$S(\mathrm{c}) = (\mathrm{x} - \Phi(t)\mathrm{c})^T(\mathrm{x} - \Phi(t)\mathrm{c}),$$

Where:

- $\Phi(t)$ represents the matrix of basic functions at the discrete time points t_j.
- $\mathrm{c} = (c_0, c_1, \ldots, c_B)^T$ represents the vector of coefficients to be estimated.

3.1.4 Inner Product for Functional Data

The inner product is used to compute the projections of the data onto the basis functions using the least squares method. The inner product between two functions $u(t)$ and $v(t)$ is given by:

$$\langle u, v \rangle = \int_I u'(t) v(t) \, dt. \tag{2}$$

Where:

- $\langle u, v \rangle$ represents the inner product of the two functions $u(t)$
- $v(t)$, $u'(t)$ is the derivative of $u(t)$ (if needed for the particular function space)
- The integral is taken over the interval I.

The inner product is used to calculate the projection of the observed data x_j onto the basis functions $\varphi_b(t)$. to ensure the smoothness of the function.

3.1.5 Reconstructing the Continuous Function

After estimating the coefficients c, the random process $x(t)$ is characterized by the following formula:

$$x(t) = \textstyle\sum_{b=0}^{B} \hat{c}_b \, \varphi_b(t), \quad t \in I. \tag{3}$$

The continuity equation for the observed data **x**.

3.1.6 Multivariate Functional Data

Multivariate functional data are handled by expanding the underlying process. Let $X(t) = \left(X_1(t), X_2(t), \ldots, X_p(t)\right)^T$ where p is a vector of random processes that are summed to the same discrete time points.

The representation of each component $X_d(t)$ for $d = 1,2,\ldots,p$ is given by:

$$X_d(t) = \textstyle\sum_{b=0}^{B_d} c_{db} \, \varphi_b(t), \quad t \in I, \quad d = 1,2,\ldots,p.$$

Where $\varphi_b(t)$ represents the basis functions of each component, and c_{db} are the coefficients of the d-th component. The multivariate functional data is represented as:

$$\mathrm{X}(t) = \sum_{d=1}^{p} \Phi_d(t) \mathrm{c}_d, \quad t \in I. \tag{4}$$

Where:

- $\Phi_d(t)$ is the matrix of basis functions for the d-th component,
- c_d is the vector of coefficients for the d-th component.

3.1.7 Matrix Representation of Coefficients

The coefficient vector $c$and the matrix $\Phi(t)$are obtained using the following:

- Coefficient Vector c:

$$\mathrm{c} = \left[c_{1B1}, c_{1B2}, \ldots, c_{pBp}\right]^T$$

- Matrix $\Phi(t)$:

$$\Phi(t) = \begin{bmatrix} \varphi'_B 1(t) & 0 & \cdots & 0 \\ 0 & \varphi'_B 2(t) & \cdots & 0 \\ & & \ddots & \\ 0 & 0 & \cdots & \varphi'_B p(t) \end{bmatrix}.$$

Multiplying $\Phi(t)$ by the coefficient vector c reconstructs the multivariate functional data:

$$\mathrm{X}(t) = \Phi(t)\mathrm{c}. \tag{5}$$

3.1.8 Model Selection Using Bayesian Information Criterion (BIC)

To determine the optimal number of basic functions B, we use the Bayesian Information Criterion (BIC) to improve and fit the model.
The formula for BIC is:

$$BIC = \ln\left(\sum_{j=1}^{J}\left(x_j - \sum_{b=0}^{B}\hat{c}_b\,\varphi_b(t_j)\right)^2\right) + (B+1)\left(\frac{\ln J}{J}\right).$$

3.1.9 Final Transformation to Functional Data

After estimating the coefficients $\hat{\mathrm{c}}$, the continuous functional data is obtained:

$$\mathrm{X}(t) = \Phi(t)\,\hat{\mathrm{c}}. \tag{6}$$

It represents the reconstructed functional data from the discrete data.

3.1.10 Principal Component Analysis for Functional Data

MFPCA is an advanced analytical statistical method that reduces dimensions and extracts main patterns from complex data containing many functional variables. These variables are described as mathematical functions that change continuously over space or over closely spaced time intervals within a specific time frame, allowing for the analysis of the variance present within the complex data.

The mathematical steps of the MFPCA method begin by identifying the principal components that explain the greatest amount of variance in the data. This is done by finding weight functions or (weight vectors) that represent these components. Where the first principal component, which represents the largest variance in the data, is extracted, followed by finding the other components with the constraint that these components are uncorrelated with the previous components. This allows for dimensionality reduction without losing the important information contained in the data.

In applications that involve variables changing continuously over time or any other continuous data, we use the MFPCA method to analyse those variables. MFPCA allows for understanding the complex relationships between variables and discovering hidden patterns that may not be visible when analysing the variables separately at discrete data points. This is achieved by transforming the data into a new set of uncorrelated principal components, ordered from greatest variance to least, while preserving the variance of the original data. If we have a random vector $X = \left(X_1, X_2, \ldots, X_p\right)' \in \mathbb{R}^p$We look for a linear combination $U_1 = u_{11}X_1 + u_{12}X_2 + \cdots + u_{1p}X_p = u_1'X$, where X is the vector of components that has the maximum variance. Where U_1 represents the first principal component, we then find a linear combination $U_2 = u_2'X$ which is unrelated to the first component U_1 and so on until we reach the k-th stage, followed by a linear combination $U_k = u_k'X$ for the k-th principal component, which has the maximum variance and is also unrelated to the previous principal components.

PCA helps understand the structural composition of the variance in the covariance matrix of one-dimensional functional data [4], [12], [13].

3.2 Functional Principal Component Estimation

In multivariate functional PCA, we aim to find the inner product:

$$U = \langle u, X\rangle = \int_I u'(t)X(t)\,dt. \tag{7}$$

Equation (5) represents the projection of the functional data onto the vector function u, which has the largest variance for all $u \in L_2^p(I)$, where $\langle u, u\rangle = 1$, and it is assumed that:

$$\lambda_1 = \sup_{u \in L_2^p(I)} \mathrm{var}(\langle u, X\rangle) = \mathrm{var}(\langle u_1, X\rangle). \tag{8}$$

Where:

- u_1 represents the first eigenfunction;
- λ_1 represents the first eigenvalue.

The first principal component is determined as the direction that maximizes the variance, defined as $U_1 = \langle u_1, X\rangle$, where $u_1(t)$ represents the eigenfunction corresponding to the first principal component.

Finally, then find the second principal component $U_2 = \langle u_2, X\rangle$ to maximize the variance $\mathrm{var}(\langle u, X\rangle)$, provided the condition $\langle u_1, u_2\rangle = 0$ (i.e., orthogonality of the first component).

3.2.1 General Principal Components

In general, the k-th principal component $U_k = \langle u_k, X \rangle$ satisfies the following:

$$\lambda_k = \sup_{u \in L_2^p(I)} \text{var}(\langle u, X \rangle) = \text{var}(\langle u_k, X \rangle).$$

Where, $\langle u_{k_1}, u_{k_2} \rangle = \delta_{k_1 k_2}, k_1, k_2 = 1, \dots, k$

$\delta_{k_1 k_2}$ is the Kronecker delta, which is:

$$\delta_{k_1 k_2} = \begin{cases} 1 & if\ k_1 = k_2 \\ 0 & if\ k_1 \neq k_2 \end{cases}.$$

Thus, the functional principal component system $\left(\lambda_k, u_k(t)\right)$ for the process $X(t)$ is defined, and we represent the process $X(t)$ as:

$$X(t) = \Phi(t)c, \quad t \in I. \tag{9}$$

Where $E(X) = 0$, $E(c) = 0$, and $\text{Var}(c) = \Sigma$. The k-th principal component $U_k^* = \langle \omega_k, c \rangle$ for this vector satisfies:

$$\gamma_k = \sup_{\omega \in \mathbb{R}^{k+p}} \text{Var}(\langle \omega, c \rangle) = \omega' \Sigma \omega. \tag{10}$$

Where:

- ω_k is the eigenvector corresponding to the k-th principal component,
- Σ is the covariance matrix of c, The k-th principal component system $\left(\lambda_k, u_k(t)\right)$ is related to the principal component (γ_k, ω_k) of the random vector c via the equation:

$$\lambda_k = \gamma_k, \quad u_k(t) = \Phi(t)\omega_k, \quad t \in I.$$

Where, $k = 1, \dots, s$, and $s = \text{rank}(\Sigma)$.

3.2.2 Principal Component Estimation from Samples

For estimating the principal components from samples, assume that we have n independent observations $x_1(t), \dots, x_n(t)$ of the random process $X(t)$. These are of the form:

$$x_i(t) = \Phi(t)\hat{c}_i. \tag{11}$$

Where $\hat{c}_i$ are the sample coefficients, and $\hat{C} = (\hat{c}_1, \hat{c}_2, \dots, \hat{c}_n)'$.

The covariance matrix $\hat{\Sigma}$ is estimated as:

$$\hat{\Sigma} = \frac{1}{n} \hat{C}' \hat{C}. \tag{12}$$

Where, $\hat{\Sigma}$ is the sample covariance matrix.

The eigenvalues $\hat{\gamma}_1 \geq \hat{\gamma}_2 \geq \cdots \geq \hat{\gamma}_s$ are the non-zero eigenvalues of $\hat{\Sigma}$, and the eigenvectors $\hat{\omega}_1, \hat{\omega}_2, \dots, \hat{\omega}_s$ are the corresponding eigenvectors.

The principal components for the random process $X(t)$ based on the sample data are:

$$\left(\hat{\lambda}_k = \hat{\gamma}_k, \hat{u}_k(t) = \Phi(t)\hat{\omega}_k\right) \qquad k = 1, \dots, s. \tag{13}$$

4 SIMULATION OVERVIEW

4.1 Simulated Functional Data and FPCA Analysis

The simulation produces artificial multivariable functional data consisting of 10 sample curves, each observed over 50 equally spaced time points in the interval [0, 1]. Three functional components are simulated to represent distinct dynamical patterns: a sinusoidal trend (variable 1), a cosine-based oscillation (variable 2), and a linear trend with noise (variable 3). These components simulate real-world scenarios such as physiological signals, environmental measurements, or sensor outputs. The discrete data are then transformed into smooth functional representations using Fourier basis extensions, with the number of basic functions chosen via the Bayesian Information Criterion (BIC) to balance model fit and complexity, as shown in Table 1. Functional principal component analysis (FPCA) is applied to extract the dominant variance patterns, as shown in Tables 2, 3, 4, and 5, and dimensionality is reduced by projecting each curve onto the leading principal components, as shown in Table 6.

Table 1: Optimal number of basis functions and BIC values.

VAR	1	2	3
Basis 5	0.5505	-0.4945	1.6726
Basis 6	0.5788	-0.4352	1.5277
Basis 7	0.657	-0.3569	1.6059
Basis 8	0.6645	-0.3233	1.5252
Basis 9	0.7427	-0.2451	1.6035
Basis 10	0.7814	-0.2426	1.5863
Optimal Basis	5	5	8

Table 2: Explained variance ratio by functional principal component.

VAR	FPC 1	FPC 2	FPC 3	Total Variance Explained
1	0.4579	0.2903	0.1521	0.9004 (90.0%)
2	0.3135	0.2649	0.204	0.7824 (78.2%)
3	0.3847	0.2156	0.1833	0.7836 (78.4%)

Table 3: FPC scores for all samples (Variable 1).

Sample	FPC1	FPC2	FPC3
1	0.01763	0.003475	-0.008379
2	-0.002226	-0.000664	0.002051
3	-0.006237	-0.000415	-0.001019
4	-0.002955	0.003093	-0.001727
5	-0.000268	0.017201	0.00576
6	0.016524	-0.006109	0.002501
7	-0.009067	0.00712	-0.004701
8	-0.000934	-0.006015	0.012101
9	-0.014809	-0.00873	-0.004964
10	0.002341	-0.008957	-0.001623

Table 4: FPC scores for all samples (Variable 2).

Sample	FPC1	FPC2	FPC3
1	0.005197	0.004723	0.007229
2	-0.003033	0.003634	-0.000094
3	0.006536	-0.007081	-0.000759
4	-0.002312	0.003863	0.004948
5	0.00017	0.00388	-0.000792
6	-0.000846	-0.003144	-0.005397
7	0.000876	-0.008372	0.004618
8	-0.013045	-0.002258	-0.000124
9	0.003094	-0.000935	-0.003169
10	0.003365	0.00569	-0.00646

Table 5: FPC scores for all samples (Variable 3).

Sample	FPC1	FPC2	FPC3
1	0.004874	-0.000342	0.008137
2	-0.000907	-0.003172	-0.003756
3	-0.003288	0.004258	0.001245
4	-0.000332	0.006735	-0.005194
5	-0.007451	-0.001239	0.001725
6	0.006316	-0.004657	-0.000756
7	-0.001544	-0.002391	-0.00283
8	-0.006007	-0.00526	0.000261
9	-0.002004	0.005087	0.003075
10	0.010343	0.000979	-0.001905

4.2 Analysis of Results

The results demonstrate a successful application of Functional Data Analysis (FDA) from data representation to dimensionality reduction. First, the Bayesian Information Criterion (BIC) effectively selects the optimal number of Fourier basis functions: 5 for Variables 1 and 2, and 8 for Variable 3. This is consistent with the nature of the variables: Variables 1 (sinusoidal) and 2 (cosine-based) are smooth and periodic, so they can be accurately represented with fewer basis functions, whereas Variable 3 follows a linear trend with added noise, which is less periodic and requires more basis functions (8) to capture its shape accurately. This demonstrates that BIC adapts to the complexity of each functional variable, avoiding both underfitting and overfitting.

After functional representation, Functional Principal Component Analysis (FPCA) is applied. The results show that the first three principal components explain a high percentage of total variation: 90.0% for Variable 1, 78.2% for Variable 2, and 78.4% for Variable 3 (see Figure A4 in the Appendix). Figures A1-A3 in the Appendix illustrate the functional principal components for each variable, highlighting the main patterns captured by FPCA. This indicates that most of the information in the original data is preserved in just a few components, enabling significant dimensionality reduction without major loss of insight.

The first component (FPC1) typically represents the main pattern – such as amplitude in oscillatory signals or overall slope in linear trends – while FPC2 and FPC3 capture secondary variations like phase shifts, curvature, or local fluctuations. Most samples have values close to zero when examining FPC scores, which indicates they follow the average pattern. However, some samples show varying degrees of deviation: for example, sample 6 in Variable 1 has a high positive FPC1 score, indicating a curve with above-average amplitude, while sample 9 shows the opposite. In Variable 3, sample 10 has the highest FPC1 score, reflecting a steeper upward trend, whereas sample 5 is flatter. Other deviations, such as the high FPC3 scores in samples 1 and 8, indicate unique local behaviours, including late peaks or noise patterns.

In general, the final reduced data matrix (10×9) consolidates all the scores into an interpretable and visualisable compact representation, where each sample is described by nine meaningful features, three for each variable. Table 6 presents this matrix, combining the top three FPC scores from each of the three functional variables into a single 9-dimensional feature space. This transformation reduces the original $10 \times 50 \times 3 = 1500$ discrete observations into a compact, structured, and interpretable format. The integration of scores allows for multivariate analysis – for example, detecting samples that simultaneously exhibit high amplitude in Variable 1, low offset in Variable 2, and steep slope in Variable 3. Sample 10, for instance, shows positive FPC1 scores in all three variables, indicating an above-average profile in overall magnitude, phase, and trend. In contrast, Sample 9 exhibits mostly negative scores, representing a below-average profile. Reducing high-dimensional data to a low-dimensional representation preserves the fundamental dynamics of the system and is crucial for clustering, classification, and other downstream analyses, demonstrating the practical value of FDA.

Table 6: Final reduced data matrix (10 × 9).

	V1-FPC1	V1-FPC2	V1-FPC3	V2-FPC1	V2-FPC2	V2-FPC3	V3-FPC1	V3-FPC2	V3-FPC3
1	0.0176	0.0035	-0.0084	0.0052	0.0047	0.0072	0.0049	-0.0003	0.0081
2	-0.0022	-0.0007	0.0021	-0.003	0.0036	-0.0001	-0.0009	-0.0032	-0.0038
3	-0.0062	-0.0004	-0.001	0.0065	-0.0071	-0.0008	-0.0033	0.0043	0.0012
4	-0.003	0.0031	-0.0017	-0.0023	0.0039	0.0049	-0.0003	0.0067	-0.0052
5	-0.0003	0.0172	0.0058	0.0002	0.0039	-0.0008	-0.0075	-0.0012	0.0017
6	0.0165	-0.0061	0.0025	-0.0008	-0.0031	-0.0054	0.0063	-0.0047	-0.0008
7	-0.0091	0.0071	-0.0047	0.0009	-0.0084	0.0046	-0.0015	-0.0024	-0.0028
8	-0.0009	-0.006	0.0121	-0.013	-0.0023	-0.0001	-0.006	-0.0053	0.0003
9	-0.0148	-0.0087	-0.005	0.0031	-0.0009	-0.0032	-0.002	0.0051	0.0031
10	0.0023	-0.009	-0.0016	0.0034	0.0057	-0.0065	0.0103	0.001	-0.0019

5 CONCLUSIONS

The simulation results of our research show that functional data analysis (FDA) is a useful tool for converting high-dimensional, multivariate data into a simple, clear, low-dimensional representation while retaining the dynamic characteristics of the original data. That the criterion of information-theoretic virtualization turned out to optimally choose the number of base States, thereby achieving a kind of balance in the clarity of the model, balancing the accuracy of the model and complexity.

Functional principal component analysis explained the bulk of the data variance (between 78% and 90%) based on only three principal components, demonstrating the model's ability to capture primary patterns such as oscillations, linear trends and local variations.

6 RECOMMENDATIONS

In future research, researchers recommend conducting sensitivity analysis through simulated experiments or real data using various sample sizes and variable time intervals. This process will help to identify and limit the possibility of stability and accuracy of the model, in addition to increasing the researchers ' confidence in the practical application of the model across a variety of data situations. Sensitivity testing can also help in the real detection of any problems with generalization or overgeneralization of these cases, which directs to the improvement of the models and methods used.

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APPENDIX

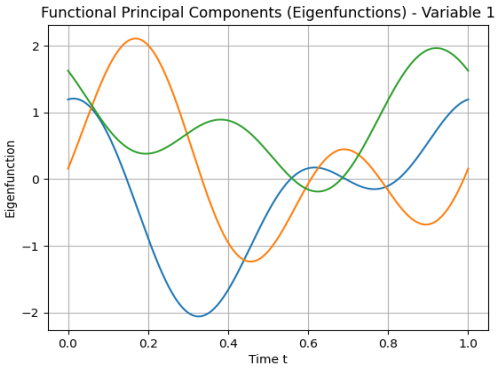


Figure A1: Functional principal components for Variable 1.

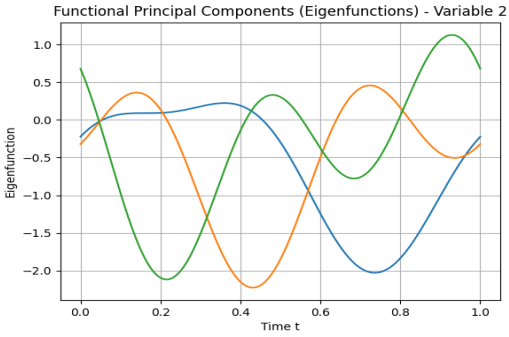


Figure A2: Functional principal components for Variable 2.

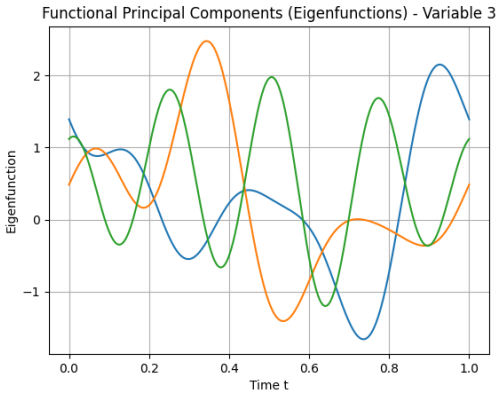


Figure A3: Functional principal components for Variable 3.

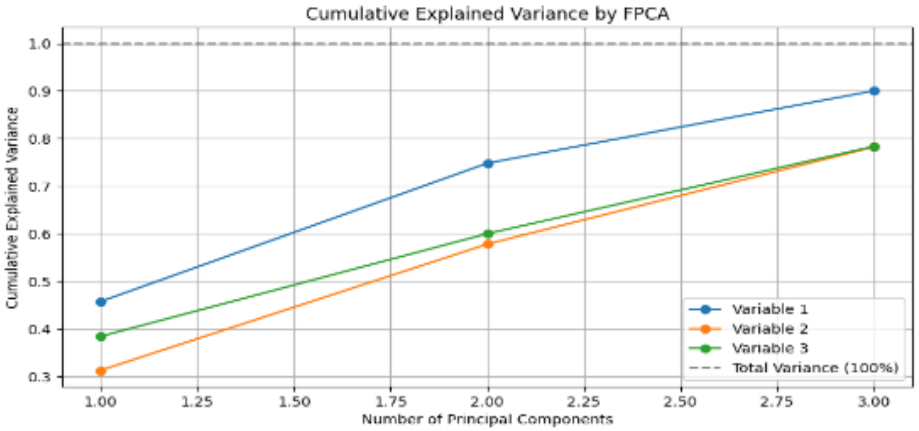


Figure A4: Cumulative explained variance by FPCA.

Hybrid ARMAX-ANN Model for Temperature Forecasting

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Keywords ANN Model, ARMAX Model, Hybrid Models, MSE.

Abstract: Many researchers have been interested in improving known forecasting methods using several methods, including hybridizing time series models with one, two, or more models in order to obtain greater accuracy in predicting the data of the series to be predicted. Therefore, our research is an extension of the researchers who preceded us in order to provide forecasting methods that have an impact in the field in which they are used. Therefore, our study focused on the ARMAX model, as it is a model that combines time series models and a regression model, and it becomes more effective when it is hybridized with one of the artificial intelligence models (ANN) in order to improve forecasting results, which are considered important in decision-making and in all areas of life, including the average temperature in Basra Governorate. A comparison was made between the ARMAX models, the ANN model, and the ARMAX-ANN hybrid model in order to predict temperatures for the years (2024-2028), as it became clear that the hybrid model is better at forecasting using the MSE criterion.

1 INTRODUCTION

Researchers' pursuit of highly accurate forecasts is crucial, as it reduces risk and provides early warning to decision-makers regarding potential disruptions in the near future, enabling them to avoid them in various sectors. Although the ARIMAX model is excellent at predicting time series, these models may not provide highly accurate forecasts. This is because time series data contains two components: one linear and the other nonlinear. This means that ARIMAX models or neural networks alone may fail to model linear and nonlinear relationships. Therefore, we will use hybrid models, which are flexible and capable of handling different types of data. The forecasting process relies on a scientific and precise approach to predicting and obtaining future values. Therefore, this research aims to compare the ARIMAX model, the ANN model, and the hybrid model that combines them to determine which model is best for temperature forecasting. Based on the MAPE metric, it was found that the best forecasting model is the hybrid model.

2 PREVIOUS STUDIES

We will present some previous studies using the ARMAX model. Among these studies is the 2016 study by Muhammad & Fakhri, which aimed to achieve higher forecasting accuracy by using ARMAX models. They used a series of exogenous variables and a series of past errors, then used the best estimate method to predict the maximum temperature for the next 30 days [1]. Another study by Alkali & others in 2019 aimed to compare the ARIMA and ARIMAX models to predict residential property prices in Abuja, Nigeria, using quarterly data on average home sales prices from the first quarter of 2000 to the last quarter of 2017. The results showed that the ARMAX model outperformed ARIMA models in general [2]. Another study by Musa and others in 2021 aimed to study the impact of independent variables, such as rainfall, temperature, and humidity, on selected agricultural crops using the ARIMAX model and then predict them [3].

3 RESEARCH PROBLEM

The prediction process using some single models, such as the ARIMAX model or the ANN model, is considered insufficient, as the predictions do not provide high accuracy in most c Both linear and nonlinear relationships are present in this data. However, if the used series model is hybridized with an artificial intelligence (AI) prediction model, the hybrid model will perform better, and we will obtain more accurate predictions for the time series than the single models.

4 OBJECTIVE

To improve the ARMAX prediction model by using the hybridization method with an ANN model, one of the artificial intelligence methods, to predict average temperatures in Basra Governorate.

5 THEORETICAL ASPECT

5.1 The ARMA Model

It is called the Autoregressive Moving Averages (ARMA) model [3], and it is a special case of the Autoregressive Integrated Moving Means (ARIMA(p,d,q) model. When the series is stationary (d=0), it is written as ARMA(p,q), where p is the autoregressive order (AR) and q is the moving mean order (MA). The mathematical form of the ARMA model is: ases. Because the time series contains two parts, one linear and the other non-linear, they:

$$y_t = \delta + \sum_{i=1}^{p} \emptyset_i y_{t-i} + e_t - \sum_{j=1}^{q} \theta_j e_{t-j} \dots\dots(1)$$

5.2 ARMAX Model

The ARMAX (AutoRegressive Moving Average with eXogenous inputs) [4], [1] model is an extension of the ARMA model that incorporates external (exogenous) variables. In this model, the time series Y_t is expressed as a function of its past values, past error terms, and exogenous variables. The general form of the ARMAX model is given by:

$$y_t = \delta + \sum_{i=1}^{p} \emptyset_i y_{t-i} + e_t - \sum_{j=1}^{q} \theta_j e_{t-j} + \sum_{k=1}^{r} \pi_k X_{k,t-1} \dots\dots$$

- Yt: The value of the observed phenomenon at time t;
- δ: The constant;
- $\emptyset_i$: Autoregressive (AR) model parameters;
- θ j: Moving Average (MA) model parameters;
- π _k: The exogenous variable parameters;
- et: The random error.

5.3 Artificial Neural Networks (ANNs)

Artificial neural networks (ANNs) [5] are considered one of the most important and widely used methods of artificial intelligence. Their concept is derived from simulating the human brain's ability to recognize patterns and distinguish objects using computational models. This approach is based on a learning process inspired by the human brain, which relies on past experiences to improve performance in future tasks. The following Figure 1 illustrates a basic operating unit of a neural network.

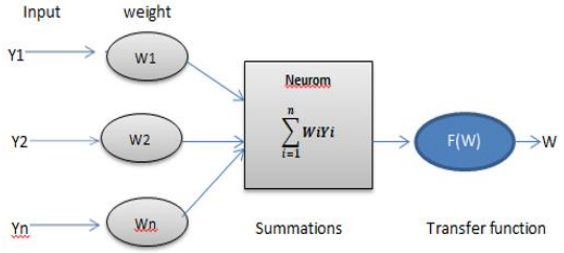


Figure 1: Model of an operating unit.

Each of the operating units contains one or more input paths through which information or data is transferred from the external world to the operating unit, which in turn performs a simple aggregation process. The information is then transformed after the aggregation process using an activation function known as a transfer function. It is then transferred as output through the output path. Mathematically, each artificial neuron will receive a few inputs (Y1, Y2,…, Yn), similar to the branches of neurons in humans. Each of these inputs is then multiplied by weights (W1, W2,…, Wn). These weights express the degree of importance of the inputs. The summed result ($\sum wiyi$) is then processed using the transfer function F(y) to obtain the final output.

5.4 Learning of the Neural Network

Learning of a neural network can be defined as the process by which a neural network can modify itself

in response to inputs to produce the desired output [3], [6]. It can also be defined as the process of acquiring knowledge using input data. During the learning process, the connection weights are adjusted, and this process continues until the network's outputs approximate the actual outputs. The process of teaching or training the network involves discovering typical relationships present in the input data, using one of the following methods.

5.4.1 Supervised Learning

This method is one of the most widely used methods for training neural networks. The network compares the results obtained for external variables with the actual input variables for each input sample. Based on this, the network's weights are adjusted to reduce errors. This process is repeated several times until acceptable results are achieved.

5.4.2 Unsupervised Learning

This method is similar to supervised learning, but differs in that the samples used in the training process do not include any values of external variables. Instead, the training process consists of input data, which consists of several groups. The network is trained to detect the most important features not apparent in the groups. These features are then used to divide the input data into groups that are distinct from each other, but similar within each group.

This method is a combination of the two previous methods. It does not use the values of external variables in the training process, as in unsupervised training, but it does indicate the validity of the network's results, as in supervised training.

6 TYPES OF NEURAL NETWORK STRUCTURES

There are several types of neural network structures [6], [7], which we will briefly explain:

6.1 Single-Layer Feed-Forward Network

This network is the simplest type of artificial neural network structure and is considered one of the most common types. It is the basic model upon which other single-layer network structures are built. It is also the simplest type of feed-forward neural network, as information is transferred directly from the input layer to the output layer. The network is trained via supervised learning. Figure 1 above illustrates the structure of this network. The learning process in this network is carried out through the following steps:

Setting random initial values for the weights (W1, W2,…, Wn) as well as an initial value for the threshold value (θ) within the range [-0.5, 0.5].

This step is called the activation process. Each processing unit receives multiple input signals and calculates the weighted sum of these inputs using the following sum function:

$$Y = \sum_{i=1}^{n} WiYi \ldots. \quad (3)$$

Where Y is the net weighted input to the neuron, Wi is the weights, Yi is the input value, and n represents the number of inputs to the neuron.

The output is calculated according to the following formula:

$$W(K) = STEP\left[\sum_{i=1}^{n} Wi(K)Yi\,(K) - \theta\right] \ldots\ldots\ldots\ldots (4)$$

The activation function is called the step function. There are many other activation functions, such as the sign function, the linear function, and the sigmoid function. The latter is the most commonly used because of its ease of differentiation and ease of calculating the slope.

The activation function is called a step function. There are many other activation functions, such as the sign function, the linear function, and the sigmoid function. The latter is the most commonly used due to its ease of differentiation and ease of calculating the slope.

6.2 Multilayer Feedforward Network

This artificial multilayer network is used to solve many complex problems that cannot be solved by a single-layer network. It propagates input signals forward from one layer to the next, without going backward. However, its drawback is that it takes longer to complete. Figure 2 illustrates the network's operation:

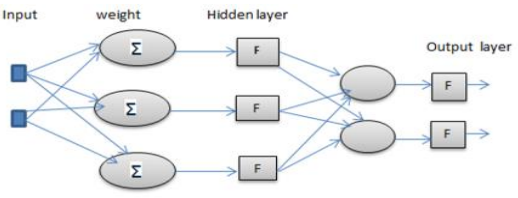


Figure 2: Multi-layer feed-forward network.

6.3 Multi-Layer Feedback Network

This type of network differs from the previous multi-layer network in that it contains at least one feedback loop. Unlike the previous feed-forward network, the error between the network's output and the actual output is calculated. However, the error is also fed in the opposite direction, i.e., in the opposite direction of the inputs, to adjust the weights and reduce the error.

7 HYBRID MODEL

The hybrid model [8], [9] is formed by combining a linear model with another non-linear model to address shortcomings in the individual model, whether linear or non-linear. This reduces errors resulting from using an inappropriate model, and it is an effective means of improving future predictions.

7.1 Steps for Constructing the Hybrid Model

1) Assume that the time series (yt) is a combination of two parts: the first is the linear autocorrelation part (Lt) and the second is the non-linear part (Nt).
2) We first use the ARMAX model to predict temperature values, then subtract the predicted values from the actual values to obtain the residual, which is recorded as a nonlinear component.
3) The residual is fed into the ANN or artificial neural network (ANN) model for prediction.
4) We obtain the predicted values for the hybrid model as follows:

$$Y_t = L_t + N_t \ldots. \quad (5)$$

8 MEAN SQUARE ERROR

The mean square error (MSE) [1], [8] is used to measure the accuracy of estimation or forecasting and is defined as:

$$\mathrm{MSE} = \frac{\sum_{i=1}^{n}(\mathrm{Pi} - \mathrm{Ai})^2}{n}. \quad \ldots \quad (6)$$

Where Ai denotes the actual (observed) value, Pi is the predicted (estimated) value, and n is the sample size.

9 PRACTICAL ASPECT

A practical analysis was conducted to predict temperatures in Basra Governorate by month using the ARMAX model, first relying on the AR and MA models, and the external variable, rainfall, for the years 1974-2023. Then, a neural network model was used, and the prediction was improved using the ARMAX-ANN mixed model, as follows:

Determining the rank of the ARMA(p, q) model: Before using the ARMAX model, it is necessary to know the stability of the time series of the two dependent variables, temperature and the external variable, rainfall. Using the unit root test, Table 1 was obtained:

Table 1: Unit root test for the dependent variable, average temperature in Basra (see Appendix, Table A1).

Null Hypothesis: Y has a unit root			
Exogenous: Constant			
Lag Length: 3 (Automatic - based on SIC, maxlag=19)			
		t-Statistic	Prob.*
Augmented Dickey-Fuller test statistic		-3.64623	0.0058
Test critical values:	1% level	-3.440275	
	5% level	-2.865810	
	10% level	-2.569102	
*MacKinnon (1996) one-sided p-values.			

From Table 1, the Augmented Dickey-Fuller test statistic is less than the critical values at all significance levels, and the corresponding p-value (0.0058) is less than 0.05. Therefore, the null hypothesis of a unit root is rejected, indicating that the dependent variable (average temperature) is stationary at level.

Table 2: Unit root test for the external variable: average rainfall in Basra (see Appendix, Table A2).

Null Hypothesis: X has a unit root			
Exogenous: Constant			
Lag Length: 8 (Automatic - based on SIC, maxlag=19)			
		t-Statistic	Prob.*
Augmented Dickey-Fuller test statistic		-3.682989	0.0046
Test critical values:	1% level	-3.440354	
	5% level	-2.865845	
	10% level	-2.569121	
*MacKinnon (1996) one-sided p-values.			

Similarly, the results in Table 2 show that the p-value (0.0046) is less than 0.05, leading to the rejection of the null hypothesis. Thus, the external variable (average rainfall) is also stationary at level.

The next step after stabilizing the variable at a difference of 0, is to determine the degree of both p and q in the ARMA model (Table 3):

By drawing the autocorrelation function and the partial autocorrelation function:

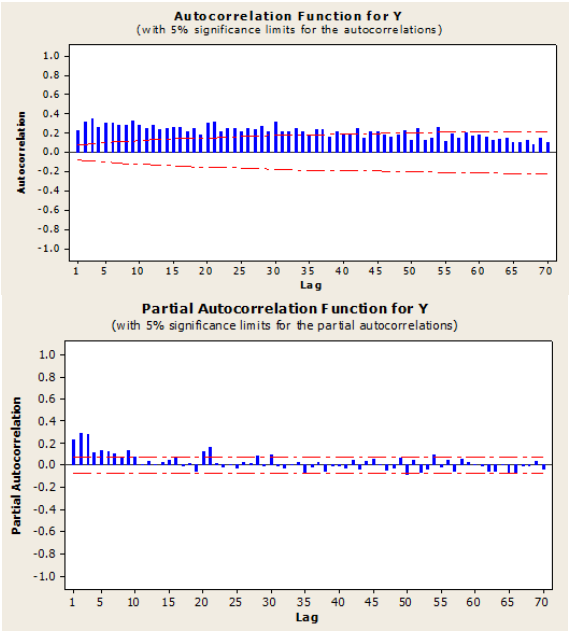


Figure 3: Autocorrelation and partial autocorrelation function of the dependent variable.

Figure 3 presents that the proposed model is ARMA (p, q). Therefore, several models were nominated, and it turned out that the best model is ARMA(1, 0) according to the MSE criterion:

Table 3: Comparison between ARMA models.

MSE	The Model
2.94	ARMA(1,0)
30.2	ARMA(0,1)
3.07	ARMA(2,0)
15.7	ARMA(0,2)
3.78	ARMA(1,2)
2.99	ARMA(2,1)
3.1	ARMA(2,2)

The results of ARMAX model estimation are presented in Figure 4.

From Figure 4, we note the significance of the estimated coefficients for the external variable, as well as the significance of the AR coefficient. The sign of the parameter for the variable coefficient is negative, which confirms the negative or inverse relationship between temperature and rainfall. Furthermore, the model explains approximately 96% of the changes in the temperature variable, which is a high percentage and confirms the model's predictive ability.

The forecasts for the years 2024-2028 are prepared monthly, as shown in Table 4 and Table 5. The result of ANN model estimation:

Dependent Variable: Y
Method: ARMA Maximum Likelihood (OPG - BHHH)
Date: 09/01/25 Time: 02:31
Sample: 1970M01 2023M12
Included observations: 648
Convergence achieved after 13 iterations
Coefficient covariance computed using outer product of gradients

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	24.80536	3.552722	6.982072	0.0000
X	-0.007068	0.003121	-2.264740	0.0239
AR(1)	0.979614	0.008476	115.5721	0.0000
SIGMASQ	3.485951	0.126536	27.54916	0.0000

R-squared	0.959142	Mean dependent var	26.11034
Adjusted R-squared	0.958952	S.D. dependent var	9.243956
S.E. of regression	1.872860	Akaike info criterion	4.103917
Sum squared resid	2258.896	Schwarz criterion	4.131534
Log likelihood	-1325.669	Hannan-Quinn criter.	4.114631
F-statistic	5039.312	Durbin-Watson stat	2.684213
Prob(F-statistic)	0.000000		

Inverted AR Roots	.98

Figure 4: ARMAX model estimation.

A neural network model was used to predict average temperatures. A feedback network with a hidden layer containing (30) nodes was used to build a model used for time series prediction. Data was fed into the artificial neural network, as shown in the Figure 5.

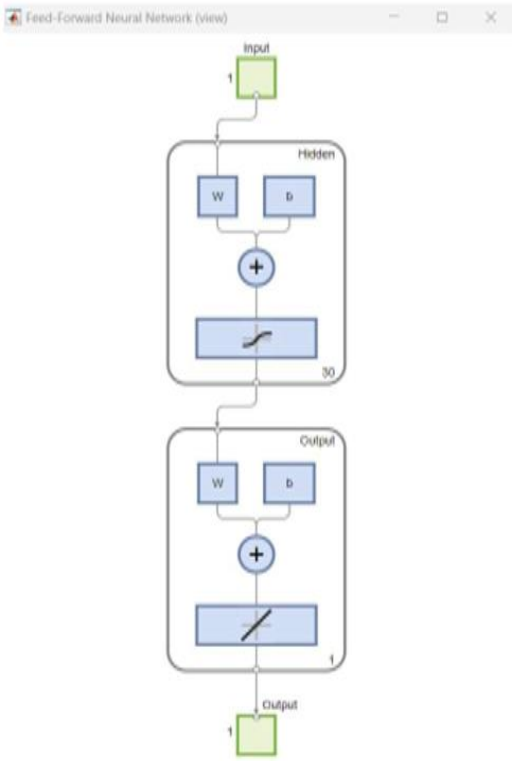


Figure 5: Artificial neural network architecture.

Through the Figure 5 and Figure 6, we notice that the input variables are linked to the hidden layer nodes, which number (30) nodes, and both of them are linked to the output node, and the strength of the relationship between the nodes, whether for input or output, is determined through the weight values (Wij), which are given initially in order for the network to be trained on them through the process of back-emission of the data.



Figure 6: Training results.

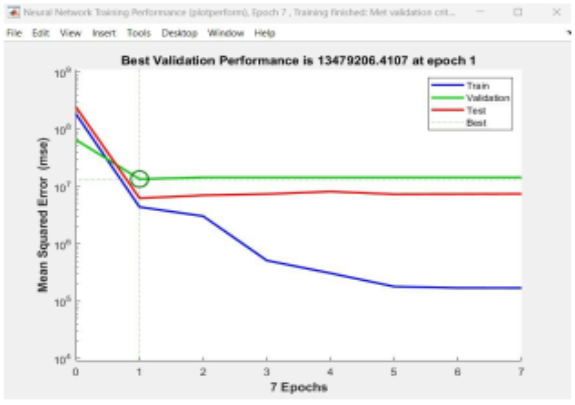


Figure 7: Best Validation Perform.

The data was divided into a training portion, which constitutes 60% of the original data, and a 20% portion for testing and validation of the robustness of the model outputted by the network. The learning parameter was set at 1% (alpha = 0.01). Figure 7 shows that the lowest error rate is achieved at iteration 107 during the neural network training process.

The Figure 7 shows that the slope value is equal to (0.0091) and will decrease as the number of training cycles for the network increases. As it decreases, the network learns more and more, thus decreasing the error rate (Mu = 0.001). The validation test is equal to (1) over (7) cycles. From the figure above, the errors generated by the neural network are normally distributed relative to the data that was trained and tested. This is a clear indication that the errors are acceptable, as they are normally distributed.

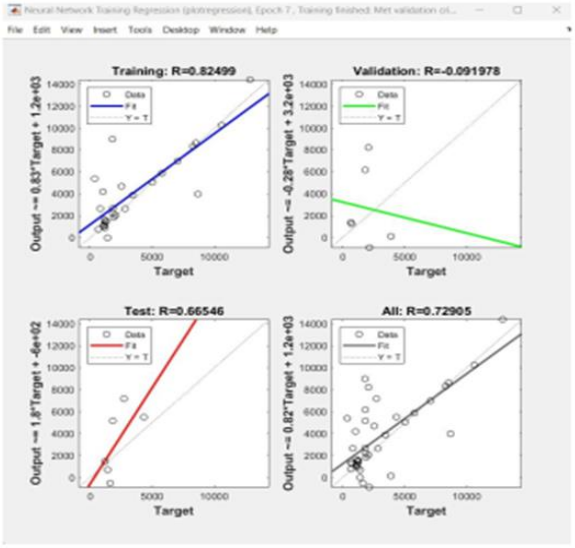


Figure 8: ANN Training regression (plot regression).

The Figure 8 shows that the training ratio was 0.82499 for the network sample, which consisted of 70% of the data. The testing ratio was 0.6654, which examines the samples, and the total ratio was 0.729.

The neural networks were predicted, and the mean square error was obtained with a value of 3.318782.

10 HYBRID MODEL

The errors generated by the ARMAX model were entered into the neural network, and the errors were obtained and combined with the predicted values of the ARMAX model to obtain the results of the hybrid model. The mean square error was calculated, and its value was 3.113275.

Table 4: Forecasting by using HYBRID MODEL for the years 2024-2028 by month.

Month of (2024)	Prediction value	Month of 2025	Prediction value	Month of2025	Prediction value	Month of 2025	Prediction value	Month of 2025	Prediction value
1	15.26213	1	17.30866	1	18.9109	1	20.1653	1	21.14737
2	15.45245	2	17.45766	2	19.02755	2	20.25663	2	21.21887
3	15.63892	3	17.60366	3	19.14185	3	20.34611	3	21.28893
4	15.82163	4	17.7467	4	19.25384	4	20.43379	4	21.35758
5	16.00065	5	17.88686	5	19.36357	5	20.5197	5	21.42483
6	16.17606	6	18.02418	6	19.47109	6	20.60387	6	21.49073
7	16.34793	7	18.15874	7	19.57643	7	20.68634	7	21.5553
8	16.51632	8	18.29058	8	19.67965	8	20.76715	8	21.61857
9	16.68132	9	18.41975	9	19.78078	9	20.84633	9	21.68055
10	16.84299	10	1854632	10	19.87987	10	20.92391	10	21.74129
11	17.00139	11	18.67034	11	19.97696	11	20.99992	11	21.8008
12	17.15659	12	18.79185	12	20.07209	12	21.0744	12	21.85911

Table 5: Forecasting by using ARMAX for the years 2024-2028 by month.

Month of 2024	Prediction value	Month of 2025	Prediction value	Month of 2026	Prediction value	Month of 2027	Prediction value	Month of 2028	Prediction value
1	15.2853	1	17.4627	1	19.1849	1	20.55937	1	21.66145
2	15.4955	2	17.6217	2	19.3116	2	20.6607	2	21.74295
3	15.6932	3	17.7777	3	19.4359	3	20.76019	3	21.82301
4	15.8857	4	17.9307	4	19.5579	4	20.85786	4	21.90165
5	16.0747	5	18.0809	5	19.6776	5	20.95377	5	21.97891
6	16.2601	6	18.2282	6	19.7951	6	21.04794	6	22.05481
7	16.4420	7	18.3728	7	19.9105	7	21.14042	7	22.12937
8	16.6204	8	18.5146	8	20.0237	8	21.23123	8	22.20264
9	16.7954	9	18.6538	9	20.1348	9	21.3204	9	22.27463
10	16.9671	10	18.7904	10	20.2439	10	21.40798	10	22.34536
11	17.1355	11	18.9244	11	20.3510	11	21.49399	11	22.41487
12	17.3007	12	19.0559	12	20.4561	12	21.57847	12	21.89218

We note that using the hybrid model led to a reduction in the mean square error value. Therefore, it was used to predict the years 2024-2028 by month, and the following results were obtained in Table 5.

11 CONCLUSIONS

The results of the unit root test are presented in Table 1. The findings indicate that the ARMA(1,0) model is the most appropriate among the considered ARMA models. Furthermore, the neural network model demonstrates superior forecasting performance compared to the ARMA model, as evidenced by the mean square error (MSE) criterion. In addition, the ARMA–ANN hybrid model further improves forecasting accuracy, as reflected by a reduction in MSE values. Based on the forecasting results, an increase in temperatures in the coming years in Basrah Governorate is observed. These results highlight the importance of employing hybrid models in forecasting applications. Moreover, it is noted that predictive efficiency in time series analysis decreases when the data contain nonlinear components.

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APPENDIX

Table A1: Average temperature in Basra.

12.6	21.4	25.3	30.1	33.4	33.9	32.4	29.7	26.3	20.1	16.6	12.9
12.6	19.7	25	31.3	33.5	33.6	31.6	31.5	23.4	19.4	14.6	12.7
10.1	18.3	26.6	30.8	34.7	33.1	33.5	27.9	24.5	18.2	12.1	10.3
12.9	17.4	27.3	31.9	35.2	34.1	32	30.4	24.8	18.9	16.8	10.8
12.4	20.3	25.7	31.5	33.6	33.9	33.2	30.2	23.5	19.3	13.2	10.5
12.1	18.9	24.1	32.7	33.7	34.9	33.4	30.5	24.9	18.5	13.9	11
15.5	19.4	27	30.7	33.2	33.2	33.2	28.8	24	16.6	13.2	12.2
15	18.2	24.6	32	34.7	34.5	33.7	31.3	24.6	20.9	16.9	10.1
15.9	15.6	26.5	30.7	32	35	32	29.9	25.2	19.9	16	13.4
13.2	20.3	27.3	32.8	34.3	34.3	34.1	30.1	26	19.5	17.3	14
13.7	20.7	26.5	31.7	34.9	37.4	35.3	30.8	26.3	20.2	13.8	12.1
11.4	16.3	26.9	34.3	34.1	36.1	34.8	31.8	26.2	17.2	11.9	12.3
14.7	21.5	25.1	31.7	35.2	36.8	34.8	31.8	23.7	17.2	13.5	10.1
12.1	20.1	25.8	32.6	33.6	37.4	34.2	30.2	26.5	20.4	15.6	12.7
13.7	20.7	25.9	32.8	37.4	35.5	34.7	32.4	25.6	18.4	13.7	14.2
12.2	17.9	29.6	34.9	37.7	37.9	34.2	31.8	25.6	19	15.1	12.7
14.9	19.6	26.9	33.4	37	37.5	35.3	34.1	25.4	18.7	17.3	12.6
13.3	18.2	27.9	32.8	35.4	36.6	34.4	30.7	24.5	18.6	14.4	11.3
12.9	20.2	27.6	32.7	37.1	38.2	34.2	31.7	26.7	18.9	11.3	9.2
15.5	20.9	28.1	32.5	35.9	38.4	35.9	33.3	25.7	19.5	14.4	10.9
14.4	21	26.6	32.3	35.6	36.6	35.5	29.8	26.7	18.9	13.4	11.9
13	19.3	26.4	33.9	36.7	36.1	35.7	30.7	24.7	15.8	12.7	9.5
16	19.2	28.7	33.7	37.9	38	35.8	30.8	25	19.4	13	11
11.6	21.2	28.4	34.4	36.4	37.3	36.3	32.7	28.1	20.4	15.6	15.4
13.1	19.5	27.3	33.3	37.6	37.5	36.8	32.8	25.4	20.1	16	13.7
17.5	20.3	27.3	34.2	39.3	39.9	38.2	34.2	24.9	20	16.5	13.6
13.6	20.4	28.6	34.3	36	37.8	37.6	33	24.3	17.4	13.3	14.2
16.8	22.1	27.9	35.1	39.8	38.5	38.5	33.2	26.6	18.9	15	11.7
13.9	19.8	29.7	34.7	38.9	38.3	37.9	33.7	27.1	19.3	16	14.3
14.1	18.7	27.3	33.7	39.8	40.2	37	34.2	29.8	19.7	14.4	12.5
16.9	19.4	28.8	34.9	39	38.7	36.6	33.5	29.2	22.2	16	12.5
14.3	19.8	30	34.6	37.8	39.6	36.9	33.7	25.8	21.8	15.4	12.3
14.7	20	33	34.6	38	39.7	37.8	33.8	25.8	22.2	15.3	12.5
11.5	20.8	28.9	34.1	37.2	38.8	37	33.9	26.1	19.9	16	12.4
15.9	18.8	28.1	33.5	37.8	38.8	36.4	32.9	26.9	20.4	17.3	12.6
10.4	18.8	29.5	32.4	39.2	38.1	37.7	33.9	26.6	21.3	15.3	13.1
13.6	20.3	29.4	34.4	38.8	38.2	37	34.3	25.9	19.2	14.7	12.3
13.7	19.4	27.8	35.1	38.6	38.4	37.1	33.3	26.3	20.2	14.2	9.4
15.9	20	29	33.8	37.7	37.8	37.6	33.8	25.4	19.9	16.9	11.4
15	20.4	29.9	35.6	39.7	39.3	38.3	33.3	27.7	22.3	18	15.5
12.4	17.9	29.9	34.7	39.8	39.2	36.7	33.8	26.6	19.5	14.7	13.1
15.4	21.9	29.6	34.6	39.1	40.4	38.1	34.9	26.6	18.6	14.3	12.6
16	22	30	35	38	39.7	36.7	34.8	26.6	21.2	17.4	13.5
16.3	19.4	29	35.4	38.5	38.7	37.1	34.9	26.3	21.1	17.3	13.7
12.9	20.5	31.1	36.1	40.4	40.2	37.8	34.3	27.2	21.3	17	14.1
14	19.1	28.5	34.9	40	40.3	38.3	34.2	27.3	22	17.3	13.1
15.6	20.8	29.5	36.3	40.3	41.2	38.4	34.6	28.1	21	13.5	13.5
16.2	19.8	29.9	37.5	39.3	40.1	38.8	33.3	26.4	24.2	18.3	14.5
16	20	30	38	42	40	39.6	34.4	25.5	19.2	16.1	14.5
15.1	20.2	30.6	36.5	39	39.1	39.6	34.4	25.5	19.2	16.1	14.5
14.8	21.7	27.9	36.5	38.3	41.2	38.2	33.5	25	20	16.3	14.1
15.6	21.5	29.8	35.2	41.2	41	38.2	35.8	28.9	21.8	17.7	14.3
16.9	22.3	30.9	35.6	39.8	39.8	38.9	32.7	28.5	20.1	17.4	12.9
17.5	21.4	30.7	37.3	40.5	41.1	38.3	33.1	27.2	21.6	15.5	12.7

Table A2: Rainfall in Basra.

12	11	10	9	8	7	6	5	4	3	2	1	السنوات
39.6	1.9	0	0	0	0	0	1.5	10.2	24.8	3	60.5	1970
40.6	2.9	1	1	1	1	1	2.5	11.2	25.8	4	61.5	1971
41.6	3.9	2	2	2	2	2	3.5	12.2	26.8	5	62.5	1972
42.6	4.9	3	3	3	3	3	4.5	13.2	27.8	6	63.5	1973
43.6	5.9	4	4	4	4	4	5.5	14.2	28.8	7	64.5	1974
44.6	6.9	5	5	5	5	5	6.5	15.2	29.8	8	65.5	1975
45.6	7.9	6	6	6	6	6	7.5	16.2	30.8	9	66.5	1976
46.6	8.9	7	7	7	7	7	8.5	17.2	31.8	10	67.5	1977
47.6	9.9	8	8	8	8	8	9.5	18.2	32.8	11	68.5	1978
48.6	10.9	9	9	9	9	9	10.5	19.2	33.8	12	69.5	1979
49.6	11.9	10	10	10	10	10	11.5	20.2	34.8	13	70.5	1980
50.6	12.9	11	11	11	11	11	12.5	21.2	35.8	14	71.5	1981
51.6	13.9	12	12	12	12	12	13.5	22.2	36.8	15	72.5	1982
52.6	14.9	13	13	13	13	13	14.5	23.2	37.8	16	73.5	1983
53.6	15.9	14	14	14	14	14	15.5	24.2	38.8	17	74.5	1984
54.6	16.9	15	15	15	15	15	16.5	25.2	39.8	18	75.5	1985
55.6	17.9	16	16	16	16	16	17.5	26.2	40.8	19	76.5	1986
56.6	18.9	17	17	17	17	17	18.5	27.2	41.8	20	77.5	1987
57.6	19.9	18	18	18	18	18	19.5	28.2	42.8	21	78.5	1988
58.6	20.9	19	19	19	19	19	20.5	29.2	43.8	22	79.5	1989
59.6	21.9	20	20	20	20	20	21.5	30.2	44.8	23	80.5	1990
60.6	22.9	21	21	21	21	21	22.5	31.2	45.8	24	81.5	1991
61.6	23.9	22	22	22	22	22	23.5	32.2	46.8	25	82.5	1992
62.6	24.9	23	23	23	23	23	24.5	33.2	47.8	26	83.5	1993
63.6	25.9	24	24	24	24	24	25.5	34.2	48.8	27	84.5	1994
64.6	26.9	25	25	25	25	25	26.5	35.2	49.8	28	85.5	1995
65.6	27.9	26	26	26	26	26	27.5	36.2	50.8	29	86.5	1996
66.6	28.9	27	27	27	27	27	28.5	37.2	51.8	30	87.5	1997
67.6	29.9	28	28	28	28	28	29.5	38.2	52.8	31	88.5	1998
68.6	30.9	29	29	29	29	29	30.5	39.2	53.8	32	89.5	1999
69.6	31.9	30	30	30	30	30	31.5	40.2	54.8	33	90.5	2000
70.6	32.9	31	31	31	31	31	32.5	41.2	55.8	34	91.5	2001
71.6	33.9	32	32	32	32	32	33.5	42.2	56.8	35	92.5	2002
72.6	34.9	33	33	33	33	33	34.5	43.2	57.8	36	93.5	2003
73.6	35.9	34	34	34	34	34	35.5	44.2	58.8	37	94.5	2004
74.6	36.9	35	35	35	35	35	36.5	45.2	59.8	38	95.5	2005
75.6	37.9	36	36	36	36	36	37.5	46.2	60.8	39	96.5	2006
76.6	38.9	37	37	37	37	37	38.5	47.2	61.8	40	97.5	2007
77.6	39.9	38	38	38	38	38	39.5	48.2	62.8	41	98.5	2008
78.6	40.9	39	39	39	39	39	40.5	49.2	63.8	42	99.5	2009
79.6	41.9	40	40	40	40	40	41.5	50.2	64.8	43	100.5	2010
80.6	42.9	41	41	41	41	41	42.5	51.2	65.8	44	101.5	2011
81.6	43.9	42	42	42	42	42	43.5	52.2	66.8	45	102.5	2012
82.6	44.9	43	43	43	43	43	44.5	53.2	67.8	46	103.5	2013
83.6	45.9	44	44	44	44	44	45.5	54.2	68.8	47	104.5	2014
84.6	46.9	45	45	45	45	45	46.5	55.2	69.8	48	105.5	2015
85.6	47.9	46	46	46	46	46	47.5	56.2	70.8	49	106.5	2016
86.6	48.9	47	47	47	47	47	48.5	57.2	71.8	50	107.5	2017
87.6	49.9	48	48	48	48	48	49.5	58.2	72.8	51	108.5	2018
88.6	50.9	49	49	49	49	49	50.5	59.2	73.8	52	109.5	2019
89.6	51.9	50	50	50	50	50	51.5	60.2	74.8	53	110.5	2020
90.6	52.9	51	51	51	51	51	52.5	61.2	75.8	54	111.5	2021
91.6	53.9	52	52	52	52	52	53.5	62.2	76.8	55	112.5	2022
92.6	54.9	53	53	53	53	53	54.5	63.2	77.8	56	113.5	2023

Fog Computing Integration for Real-Time Iot Data Processing

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Keywords: Fog Computing, Internet of Things (IoT), Real-Time Data Processing, Task Offloading, Energy Efficiency, Edge Computing, Security, Quality of Service (QoS).

Abstract: The rapid expansion of the Internet of Things (IoT) has created massive streams of real-time data that require processing near their sources to ensure timely and efficient responses. Traditional cloud-centric architectures struggle to meet these demands, leading to significant latency, energy overhead, and security vulnerabilities. Fog computing, by extending computational and storage capabilities toward the network edge, offers a promising solution to these limitations. This study systematically analyses recent advancements in fog-enabled IoT data processing, consolidating performance results from diverse approaches into a unified comparative framework. The proposed model balances latency, energy consumption, and operational costs, demonstrating performance gains of up to 95% in latency reduction, 65% in energy savings, and notable improvements in system security. Through detailed comparative analysis and graphical evaluation, the findings reveal that multi-layer fog architectures, when combined with adaptive scheduling and energy-aware service placement, can significantly enhance quality of service (QoS) while optimising resource utilisation. These insights provide practical guidance for designing sustainable, secure, and high-performance IoT ecosystems.

1 INTRODUCTION

The rapid proliferation of Internet of Things (IoT) devices has transformed modern digital ecosystems, enabling a wide range of applications that demand ultra-low latency, high reliability, and uninterrupted connectivity – such as autonomous transportation, remote healthcare monitoring, industrial automation, and smart city services [1]. However, traditional cloud-centric architectures struggle to meet these stringent requirements because data must travel across long network paths to remote data centres, resulting in excessive latency, bandwidth inefficiencies, and network congestion [2]. These limitations are particularly critical in Industrial IoT (IIoT) environments, where real-time decision-making is essential to ensure operational safety, process optimisation, and service continuity [3]. In addition, continuous transmission of raw data to the cloud increases operational costs, energy consumption, and environmental impact, while exposing sensitive information to privacy and security risks [4].

Fog computing has emerged as a promising paradigm to mitigate these challenges by extending computation, storage, and intelligence toward the network edge [5]. Fog nodes – including gateways, access points, and micro data centres – enable localised processing, filtering, and caching close to data sources, thereby reducing latency, improving bandwidth utilisation, and supporting more energy-efficient and context-aware operations [5], [6]. Building on this paradigm, researchers have proposed diverse fog-enabled architectures and optimisation strategies. Dynamic offloading schemes determine where tasks should be executed – locally, at fog nodes, or in the cloud – and have demonstrated up to 95% latency reduction and 67% energy savings compared with cloud-only processing [6]. Multi-layer edge–fog–cloud hierarchies have also shown substantial performance improvements; for instance, NB-IoT healthcare frameworks reported a 59.9% reduction in data transmission delay and a 38.5% decrease in execution time [3]. Meanwhile, energy-aware service placement algorithms, such as LJAYA, have achieved 31% reductions in energy consumption [4], and green demand-aware strategies have delivered up to 65% energy savings without

compromising delay performance [7]. Moreover, to address emerging security threats, machine learning-based authentication and intrusion detection techniques have achieved accuracy levels exceeding 99% in distributed fog environments [8].

Despite these advancements, most existing studies optimise isolated performance metrics in isolation – typically latency, energy consumption, or security – without providing a unified analytical framework that simultaneously considers latency, energy cost, operational expenditure, and security risk. This fragmentation makes it difficult for system architects to evaluate trade-offs holistically and design fog-enabled IoT infrastructures that are both high performing and sustainable.

To address this gap, this paper: (1) systematically reviews state-of-the-art fog computing strategies for real-time IoT data processing; (2) consolidates and compares quantitative performance results from at least eighteen peer-reviewed contributions; (3) proposes a unified mathematical cost model to balance latency, energy consumption, and operational cost in offloading decisions; and (4) identifies open challenges and key research directions with a focus on sustainability, adaptive architectures, and enhanced security. Through this comprehensive and analytically grounded assessment, the paper provides practical guidance for researchers and practitioners aiming to design secure, sustainable, and high-performance fog-enabled IoT systems.

2 RELATED WORK

2.1 Dynamic Task Offloading and Scheduling

Because fog nodes have limited resources, deciding Because fog nodes have limited computational resources, determining where to execute tasks is a critical design challenge. Sensors et al. proposed a dynamic offloading threshold scheme that incorporates Dynamic Task Scheduling (DTS) and Dynamic Energy Control (DEC) algorithms. Compared with cloud-only execution, this approach reduced latency by up to 95%, improved throughput by 71%, and decreased energy consumption by 67% [2]. The authors emphasised that fog computing alleviates high communication latency and network congestion by processing data closer to end devices [9].

Similarly, an energy-efficient IoT task scheduling framework (EEIoMT) classified tasks into critical, moderate, and normal categories and assigned scheduling weights based on latency and energy requirements. Simulation results demonstrated that EEIoMT reduced response time by 90%, network usage by 79%, cost by 80%, network latency by 65%, and energy consumption by 81% relative to cloud-based models [10].

Fuzzy-logic-based scheduling has also been explored to address uncertainty in task demands. In the Dynamic Task Allocation using Fuzzy Logic Enhanced approach (DTA-FLE), tasks are classified according to latency sensitivity using fuzzy sets. A hierarchical scheduler then assigns urgent tasks to fog nodes while forwarding non-urgent tasks to the cloud. The energy consumption of communication for a set of tasks on m resources is given by (1) [8]:

$$E_{\text{comm}} = \sum_{i=1}^{m} (P_{tx} + P_{rx})\, T_{\text{comm}}, \qquad (1)$$

where Ptx and Prx are transmission and reception power, respectively, and Tcomm is communication time. The DTA-FLE scheduler minimises both energy and delay by reducing unnecessary task migrations; at 700 tasks the algorithm achieved a delay of 24 s, compared with 132 s for a cloud-only scheduler (DTA) and 35–50 min for other heuristics [11], corresponding to an 82% latency reduction relative to DTA. Meta-heuristic optimisation has also shown promise. A modified Grey-Wolf Optimisation strategy (TS-GWO) achieved makespan reductions of 46.15% and energy savings of 28.57% relative to comparable schedulers [5]. In addition, an energy-efficient time-and-cost (ETC) constrained scheduling algorithm based on Improved Multi-Objective Differential Evolution (I-MODE) demonstrated energy savings of 14–24%, execution time reductions of 14–25%, and monetary cost reductions of 22–29% when evaluated using both synthetic and real workflow datasets [12].

2.2 Hierarchical Architectures

Fog computing architectures commonly adopt a three-layer structure comprising the device layer (sensors and actuators), the fog layer (near-edge processing nodes), and the cloud layer. Figure 1 illustrates this layered model. In an NB-IoT hybrid health-monitoring architecture, data aggregation and preliminary analytics are performed at the edge, protocol translation and temporary storage occur at the fog layer, and long-term analytics are executed in the cloud. Simulations using CloudSim and iFogSim showed that this architecture reduced NB-IoT

communication delay by 59.9% and execution time by 38.5% [3].

Energy-efficient service-placement strategies further enhance performance by assigning services based on resource availability and predicted workload behaviour, achieving energy savings of approximately 31% [4]. In telehealth-oriented IoT systems, integrating fog nodes with a hybrid cloud platform and adaptive energy-saving mechanisms resulted in a modest but meaningful 2% reduction in energy consumption [13].

Hybrid fog–edge architectures for real-time health monitoring employ rule-based filtering and lightweight machine-learning modules at the edge while delegating time-critical tasks to fog nodes. Reported outcomes include 70% latency reduction, a 30% improvement in energy efficiency, and 60% bandwidth savings relative to cloud-only configurations [14]. These systems frequently incorporate decision-tree and one-class SVM classifiers to detect anomalies and reduce unnecessary traffic. Green demand-aware schemes complement these architectures by powering down idle fog nodes, achieving up to 65% energy savings without compromising latency [15].

Additionally, a power-aware fog-supported IoT healthcare framework utilising swarm-intelligence algorithms demonstrated a 33% reduction in power consumption by optimising heterogeneous gateway deployment [16]. Energy consumption modelling for fog-enabled IoT communications further revealed that energy usage is inversely proportional to the Maximum Transmission Unit (MTU); larger MTU sizes therefore decrease transmission energy requirements.

2.3 Security and Privacy

The decentralised nature of fog computing introduces new security and privacy challenges. A machine-learning-based authentication and intrusion-detection framework that integrates elliptic-curve cryptography with a stacked ensemble classifier achieved 99.86% accuracy, 99.89% precision, 99.96% recall, and a 99.91% F1-score following secret-ID authentication [8].

An adaptive encryption framework further enhances confidentiality by using K-nearest neighbours to classify data sensitivity and applying hybrid ECC–AES encryption for critical data. Experimental evaluation reported encryption and decryption times between 9.679 ms and 67.79 ms and encryption throughput of 0.826–14.75 MB·s^{-1}. Histogram analysis yielded an NPCR of 99.349% and a UACI of 33.079%, demonstrating strong resilience against statistical attacks.

Finally, a zero-trust fog-computing framework integrating blockchain technology and software-defined networking provides continuous authentication for healthcare systems. Using 50 IoT devices and 10 fog nodes in iFogSim, the framework improved intrusion detection by 40%, enhanced data integrity by 30%, increased task completion rate by 15.29%, and reduced average response time by 39.66% [16]. These findings highlight that robust security can be achieved without compromising performance when implemented effectively at the fog layer.

3 UNIFIED OFFLOADING COST MODEL

Effective resource allocation in fog-enabled IoT systems requires jointly considering latency, energy consumption, and operational cost, as these factors collectively determine where a computational task should be executed – on the IoT device, a nearby fog node, or a remote cloud server. To formalise this decision-making process, we define a unified weighted multi-objective cost function that evaluates the suitability of assigning a task TTT to a given processing layer:

$$\text{Cost}(T) = \alpha \times L(T) + \beta \times E(T) + \gamma \times C(T)$$

Where:

- $\text{Cost}(T)$. Total cost of executing task *T;*
- $L(T)$. Total latency for executing task *T* on the selected layer (Seconds);
- $E(T)$. Energy consumption during execution and data transfer (Joules).
- $C(T)$. Operational or monetary cost of execution (Monetary units)
- α, β, γ. Non-negative weighting factors representing the relative importance of each metric, such that $\alpha + \beta + \gamma = 1$.

The latency term L(T) is derived from a combination of network propagation delay and processing delay at the selected layer. The energy term E(T) can incorporate the standard communication energy equation:

$$E\text{comm} = P_{tx} \times t_{tx} + P_{rx} \times t_{rx}$$

Where P_{tx} and P_{rx} denote transmission and reception power (watts), and t_{tx} and t_{rx} represent corresponding transmission and reception durations

(seconds). The cost term C(T) captures monetary expenditure or resource penalties associated with specific layers – for instance, pay-per-use cloud charging models or fog resource utilisation costs.

The scheduler's objective is to minimise Cost(T) across all available processing layers while satisfying capacity, QoS, and application constraints. The flexibility of the weighting coefficients allows the model to adapt to different operational priorities: life-critical healthcare services prioritise minimal latency (high α), while battery-powered IoT deployments emphasise energy efficiency (high β), and budget-sensitive scenarios assign greater significance to operational cost (high γ). By dynamically tuning these weights based on network conditions, task urgency, and resource availability, the unified cost model supports adaptive and context-aware offloading decisions in diverse IoT environments.

4 RESULTS AND COMPARATIVE ANALYSIS

This section presents a comparative analysis of various fog computing integration approaches for real-time IoT data processing. Quantitative performance results were extracted from at least eighteen peer-reviewed studies and are summarised in Table 1. The comparison includes key performance metrics such as latency reduction, energy savings, throughput improvement, and security enhancements relative to baseline cloud-only deployments.

Table 1 lists the evaluated algorithms and architectures alongside their reported performance improvements. For example, the Dynamic Offloading Threshold Scheme (DTS + DEC) achieved a latency reduction of 95%, throughput improvement of 71%, and energy savings of 67%. Similarly, the NB-IoT Edge–Fog–Cloud architecture demonstrated 59.9% delay reduction, 38.5% faster execution time, and 35.1% faster authentication.

Energy-aware scheduling frameworks also yielded notable gains. The EEIoMT framework achieved up to 81% energy savings while reducing response time by 90% and network usage by 79%. Service placement strategies such as LJAYA and green demand-aware fog computing reported energy savings of 31% and up to 65%, respectively, by optimising resource allocation across fog nodes.

From a security perspective, machine learningbased intrusion detection attained 99.86% accuracy with high precision, recall, and F1-score, while a blockchain–SDN-enabled zero-trust architecture improved intrusion detection by 40% and reduced average response time by 39.66%.

Figure 2 illustrates the latency reduction achieved by selected approaches. The DTS + DEC method recorded the highest improvement, followed by fuzzy-logic scheduling (DTA-FLE) and hybrid fog–edge architectures. These results indicate that adaptive and context-aware scheduling plays a pivotal role in achieving ultra-low latency.

Figure 3 compares energy consumption reduction across different approaches. Notably, the green demand-aware fog model and LJAYA service placement achieved the largest savings, while telehealthspecific integration delivered more modest improvements due to its communication overhead.

Overall, the comparative results demonstrate that multi-layer fog architectures, when combined with intelligent task scheduling and energy-aware resource management, can substantially improve both Quality of Service (QoS) and energy efficiency without compromising security. These findings provide strong evidence supporting the integration of fog computing into latency-sensitive and resource-constrained IoT applications.

Table 1 summarises quantitative results from the literature. Each row corresponds to a particular algo rithm or architecture and lists the reported improvements relative to baseline cloud-only execution. Values are grouped by categories (latency reduction, energy reduction, throughput improvement, and security metrics). Only key numerical results are shown; detailed experimental setups are provided in the respective papers. Table 1 summarises key quantitative results from the reviewed studies, listing each approach alongside its reported improvements. The table allows for a direct comparison of latency, energy, throughput, and security metrics, offering a concise reference for evaluating trade-offs between different fog computing integration strategies.

Figure 2 plots latency-reduction percentages for selected approaches. Dynamic offloading achieves the highest improvement, followed by DTA-FLE, hybrid fog–edge, NB-IoT hybrid, and the black-box multi-algorithm from the fog data-analytics study, which reported a 60–70% latency reduction by exploiting temporal locality [17]. Figure 3 compares energy-reduction metrics, showing that green demand-aware and LJAYA service placement achieve notable savings, while telehealth integration has modest improvement. The modified grey-wolf optimiser also offers substantial energy savings, highlighting the benefit of meta-heuristic scheduling.

Table 1: Summary of key improvements from reviewed fog and summary of key improvements from reviewed fog computing approaches computing approaches.

Ref.	Study / Approach	Methodology / Architecture	Evaluated Metrics	Improvement / Result Values	Experimental Conditions
[2]	DTS + DEC	Adaptive dynamic offloading + fog energy control	Latency, Throughput, Energy	Latency ↓95%, Throughput ↑71%, Energy ↓67%	Telehealth IoT; fog–cloud
[3]	NB-IoT Edge–Fog–Cloud (IoMT)	3-layer healthcare fog	Delay, Execution Time, Authentication	Delay ↓59.9%, Exec Time ↓38.5%, Auth Time ↓35.1%	CloudSim / iFogSim
[4]	LJAYA Service Placement	Lévy-flight JAYA optimisation	Energy, Optimisation Efficiency	Energy ↓31%, Efficiency ↑28.57%	Fog–cloud
[5]	TS-GWO	Grey-Wolf meta-heuristic scheduling	Makespan, Energy, Latency	Makespan ↓46.15%, Energy ↓28.57–80%, Latency ↓65%	Fog–cloud workloads
[8]	ML Authentication + ECC	Authentication + anomaly detection	Accuracy, Precision, Recall, F1	Acc 99.86%, Prec 99.89%, Recall 99.96%, F1 99.91%	Healthcare IoT
[10]	EEIoMT Scheduling	Priority weighted scheduling + encryption	Response Time, Network, Cost, Energy, Latency	RT ↓90%, Network ↓79%, Cost ↓80%, Latency ↓65%, Energy ↓81%	Healthcare simulation
[11]	DTA-FLE	Fuzzy-logic latency-aware scheduling	Delay, Energy	Delay ↓82% (132 s → 24 s), Energy Reduced	700 tasks
[12]	I-MODE ETC Scheduling	Multi-objective workflow optimisation	Energy, Execution Time, Cost	Energy ↓14–24%, Exec Time ↓14–25%, Cost ↓22–29%	Real + synthetic workflows
[13]	Telehealth Fog Integration	Hybrid fog–cloud healthcare	Energy	≈2% Energy Savings	Telehealth IoT
[14]	Hybrid Fog–Edge Healthcare	Rule-based + ML filtering at edge	Latency, Energy, Bandwidth	Latency ↓70%, Energy ↑30%, Bandwidth ↑60%	Real-time monitoring
[15]	Green Demand-Aware Fog	Predictive active/standby fog	Energy	Energy Savings up to 65%	Energy-constrained deployments
[16]	Power-Aware Fog Architecture	Swarm-intelligence optimisation	Power Consumption	Power ↓33%	Healthcare IoT
[16]	Zero-Trust Blockchain–SDN	Blockchain + SDN zero-trust	Intrusion Detection, Integrity, Response, Completion	ID ↑40%, Integrity ↑30%, Completion ↑15.29%, Response ↓39.66%	50 IoT devices; 10 fog nodes

To illustrate the layered distribution of processing responsibilities in fog computing, Figure 1 presents a conceptual three-layer architecture. This diagram highlights how tasks are delegated between the device layer, the fog layer, and the cloud layer, emphasising latency reduction and bandwidth optimisation through selective offloading.

5 DISCUSSION

The comparative evaluation demonstrates that integrating fog computing into real-time IoT systems consistently improves performance relative to traditional cloud-only architectures. In particular, fog-based designs significantly reduce latency, optimise bandwidth utilisation, enhance energy efficiency, and, in many cases, strengthen system security. However, the magnitude of improvement varies across architectures and depends strongly on workload characteristics, network conditions, fog resource capability, and the optimisation strategies employed.

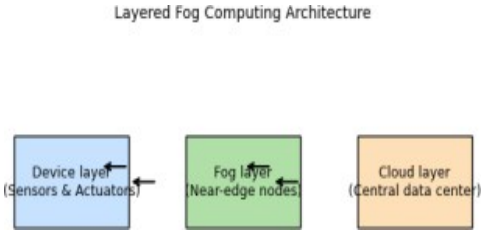


Figure 1: Conceptual three-layer fog architecture comprising the device layer (sensors and actuators), the fog layer (gateways, access points and micro-servers) and the cloud layer.

Fog-layer execution plays a central role in reducing latency by enabling localised processing and forwarding only essential information to the cloud. As illustrated in Figure 2, dynamic offloading approaches – such as the Dynamic Offloading Threshold Scheme (DTS + DEC) – achieve the most substantial latency reduction (up to 95%) because they adaptively allocate tasks based on real-time congestion, resource availability, and energy state. While these solutions also contribute to significant energy savings by avoiding unnecessary long-distance transmissions, they require accurate system monitoring and sophisticated prediction models, which introduce scheduling complexity and computational overhead.

Hierarchical fog architectures provide a balanced compromise between performance enhancement and scalability. Solutions such as NB-IoT Edge–Fog–Cloud frameworks and hybrid fog–edge designs partition workloads intelligently, assigning time-critical tasks to edge or fog nodes while offloading less urgent computation to the cloud. These systems typically achieve 60–70% latency reduction and approximately 30% energy savings. Nevertheless, their effectiveness may be sensitive to changing network topology, device mobility, and heterogeneous resource distributions.

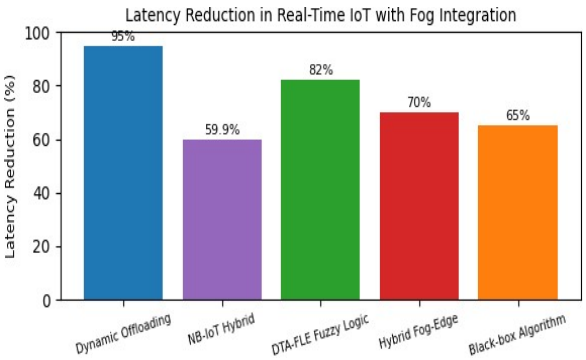


Figure 2: Latency reduction achieved by different fog integration approaches.

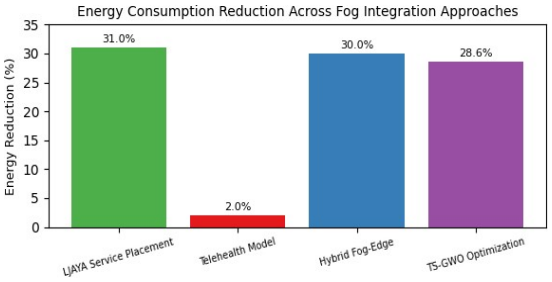


Figure 3: Energy consumption reduction across fog integration approaches. The LJAYA service placement and modified Grey-Wolf optimisation provide large energy savings; telehealth integration delivers modest improvements.

Intelligent scheduling and optimisation algorithms further strengthen fog computing performance. Approaches such as fuzzy logic-based scheduling (DTA-FLE) and meta-heuristic methods (TS-GWO) improve task allocation under uncertainty and support multi-objective optimisation. For example, fuzzy-logic-based schemes have demonstrated dramatic reductions in execution delay (e.g., from 132 s to 24 s), while Grey-Wolf-driven strategies provide favourable trade-offs between makespan and energy consumption. However, these techniques often require parameter tuning and scenario-specific calibration, which may limit their generalisability across diverse deployments.

Energy-aware frameworks represent another important design trend. Green demand-aware models and LJAYA-based service placement policies demonstrate notable efficiency gains, achieving energy reductions of 31%–65% by dynamically managing node operating states and optimising workload placement. These approaches are particularly valuable in battery-powered and remote sensing applications. However, because they primarily prioritise energy conservation, they may not deliver latency reductions comparable to aggressively adaptive scheduling techniques. Conversely, certain telehealth-oriented fog integrations yield only modest energy gains (≈2%) due to communication overhead dominating consumption.

Security-focused fog architectures further reveal that strong protection mechanisms can be integrated without incurring prohibitive performance penalties. Machine-learning-based authentication and intrusion detection frameworks achieve near-perfect accuracy, while zero-trust blockchain–SDN designs improve both data integrity and operational resilience, reducing response time by approximately 39.66%. Although these solutions may introduce additional computational and storage demand at the fog layer,

they are particularly suitable for privacy-sensitive domains such as healthcare and mission-critical industrial applications.

6 OPEN CHALLENGES AND FUTURE RESEARCH

Despite impressive progress, several challenges remain. Fog nodes are resource-constrained and often heterogeneous, making standardisation and interoperability difficult. Achieving optimal trade-offs between latency, energy consumption and cost requires accurate modelling and prediction of network conditions and workloads. Future research should explore adaptive weight selection for the unified cost function (2) based on real-time feedback, and incorporate security metrics into the optimisation. Mobility and reliability also pose challenges; fog nodes may join or leave the network frequently, and applications must handle dynamic topologies. Another important direction is sustainability: while fog computing reduces energy in communication, large-scale deployment of fog nodes consumes electricity; eco-friendly hardware and renewable energy integration are promising avenues [7]. Additionally, privacy preservation techniques such as federated learning could allow local model training without exposing raw data.

7 CONCLUSIONS

Fog computing offers a practical paradigm for real-time IoT data processing by relocating computation, storage, and analytics closer to data sources. This review systematically synthesizes quantitative evidence from at least eighteen peer-reviewed studies and confirms that fog-enabled designs can substantially outperform cloud-centric deployments in latency-sensitive settings. Reported results show improvements reaching up to 95% latency reduction, energy savings up to 65%, and measurable security enhancements when modern protection mechanisms are integrated at the fog layer.

A key contribution of this paper is the unified multi-objective offloading cost model that jointly captures latency, energy consumption, and operational cost, enabling more transparent trade-off analysis across heterogeneous IoT environments. The comparative analysis further indicates that no single solution is universally optimal: adaptive task offloading and scheduling deliver the strongest latency gains under dynamic workloads; hierarchical edge–fog–cloud architectures provide scalable workload partitioning; and energy-aware service placement and demand-aware management are most effective when power constraints dominate. In parallel, the surveyed security-aware schemes suggest that robust security and privacy controls can be incorporated without necessarily sacrificing QoS, provided that computation and protection are carefully placed within the fog layer.

Future work should prioritize intelligent orchestration that adapts offloading decisions online using prediction and learning, extends optimization objectives to explicitly include security and privacy, and strengthens mobility support and interoperability across heterogeneous nodes. Finally, sustainability remains essential; green resource management and renewable-powered fog infrastructure are promising directions for scalable and environmentally responsible IoT ecosystems.

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Existence and Stability Analysis of Nonlinear Volterra-Fredholm Integral Equations

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Keywords: Integral Equation, Volterra-Fredholm, Existence and Uniqueness of Solution, Properties of Solutions, Banach Fixed-Point.

Abstract: The aim of this paper is to prove the existence and uniqueness of a solution for a Volterra-Fredholm nonlinear integral equation in two variables under certain conditions. For instance, by using the Lipschitz condition with Banach's contraction principle under assumptions (1)-(4), a unique solution exists in Banach space Z. Moreover, we examine some fundamental characteristics of the solutions for a Volterra-Fredholm nonlinear integral equation in two variables which occur in applications, using the inequality established in [6, Theorem 1]. It has also been demonstrated that the functions and parameters included in the equation under investigation continuously influence the behavior of solutions under perturbations in parameters. This investigation may allow for the extension of findings, and the last section contains an illustrative example for the validity of the obtained results, making the method much more attractive for practical applications. The examples show the method is straightforward and effective, and the approach can also be extended to other nonlinear integral equation problems.

1 INTRODUCTION

The problem under consideration is the general nonlinear Volterra-Fredholm integral equation of the form:

$$\varphi(\ddot{\imath},\ddot{\eta}) = \mathcal{A}\left(\ddot{\imath},\ddot{\eta},\varphi(\ddot{\imath},\ddot{\eta})\right) + \\ + \int_0^{\ddot{\eta}} \int_{\mathrm{e}} \mathcal{B}\left(\ddot{\imath},\ddot{\eta},\ddot{\iota},\beta,\varphi(\ddot{\iota},\beta),(\Gamma\varphi)(\ddot{\iota},\beta)\right) d\beta d\ddot{\iota}, \quad (1)$$

Where:

$$(\Gamma\varphi)(\ddot{\imath},\ddot{\eta}) = \int_0^{\ddot{\eta}} \int_{\mathrm{e}} \mathcal{H}\left(\ddot{\imath},\ddot{\eta},\ddot{z},\ddot{\zeta},\varphi(\ddot{z},\ddot{\zeta})\right) d\ddot{\zeta} d\ddot{z} \quad (2)$$

Where $\mathcal{A},\mathcal{B}$ and $\mathcal{H}$ they are provided, and the unknown function is φ .

The name integral equation for any equation involving the unknown function $\varphi(\chi)$ under the integral sign was introduced by du Bois- Reymond in 1888 [1].

In [2] A. M. Wazwaz also presented a reliable strategy for solving a Volterra-Friedholm mixed linear integral equation in the following form:

$$u(x,t) = f(x,t) + \int_0^t \int_\Omega F(x,t,r,s)u(r,s)drds$$

$(x,t) \in \Omega \times [0,T]$,

where f , F are known functions and u is an unknown function and Ω a closed partial set of R^n , $n = 1,2,3$

The integrodifferential equations that arise in reactor dynamics and mathematical epidemiology are examined while looking at certain initial boundary value problems for parabolic partial differential equations.

In [3] H. R. Thieme considered a model for the spatial spread of an epidemic consisting of a nonlinear integral equation of Volterra-Fredholm type which has an unique solution. The author showed that this solution has a temporally asymptotic limit which describes the final state of the epidemic and is the minimal solution of another nonlinear integral equation.

In [4] O. Diekmann described, derived and analysed a model of spatio-temporal development of an epidemic. The model considered leads to the following nonlinear integral equation of Volterra-Fredholm type:

$$u(t,x) = g(t,x) + \int_0^t \int_\Omega g\big(u(t-\tau,\xi)\big)S_0(\xi)A(\tau,x,\xi)d\xi d\tau,$$

for all $(t,x) \in [0,\infty) \times \Omega$ where Ω is a bounded domain in R^n. See [5] the form (1) of the equations naturally emerges.

Equation (1) is treated as a mixed Volterra–Fredholm integral equation, as it is of Fredholm type with respect to one variable and of Volterra type with respect to the other. By modifying the method introduced in [6] (see also [7]), an existence result for equation (1) can be formulated.

The primary aim of this paper is to establish the existence and uniqueness of solutions to a nonlinear Volterra–Fredholm integral equation in two variables under suitable assumptions [8].

In [9] B. G. Pachpatte considered the integral equation:

$$u(t,x) = g(t,x) + \int_0^t \int_\Omega g\big(t,x,s,y,u(s,y)\big)dyds,$$

for all $(t,x) \in [0,T) \times \Omega = \mathrm{D}$ where Ω is a bounded domain in R^n.

2 PRELIMINARIES

Definition 2.1, [10]. Let T a mapping from a set X into itself. The mapping T has a fixed point if there exists $x_0 \in X$ such that $Tx_0 = x_0$. The most known fixed-point theorem is the Contraction Mapping Principle, due to S.

Definition 2.2, [10]. Let (X,d) be a metric space. A mapping $T: X \to X$ is Lipschitz continuous if there exists a constant $\alpha > 0$ such that $d(Tx,Ty) \leq \alpha d(x,y)$ for all $x,y \in X$.

If $0 \leq \alpha < 1$, then T is called a contraction mapping. α is called the contractively factor of T.

A (not necessarily Lipschitz) mapping $T: X \to X$ is said to have a fixed point if there exists $x \in X$ such that Tx = x.

It is not hard to see that a (nonzero) Lipschitz continuous mapping $T: X \to X$ with Lipschitz constant q is continuous. Indeed, for $\varepsilon > 0$, if we choose $0 < \delta < \frac{\varepsilon}{q}$, then

$$x,y \in X, d(x,y) < \delta \Rightarrow d(Tx,Ty) \leq qd(x,y) < q.\frac{\varepsilon}{q} = \varepsilon.$$

Definition 2.3, [11]. Let $f(n), g(n)$ be known functions, we say that $f(n) = O(g(n))$ when $n \to 0$, if there is a positive constant A then

$$|f(n)| \leq A|\mathrm{g}(n)|, \forall\ |n| > n_0.$$

3 MAIN RESULTS

Let $\mathcal{R}$ represent the set of real numbers, $\mathcal{R}_+ = [0,\infty)$, and let $\mathfrak{e} = \Pi_{i=1}^n [a_i,b_i]$ and $(a_i < b_i)$ be the specified subsets of $\mathcal{R}$. Define $C(X_1,X_2)$ as the category of continuous functions spanning the sets X_1, X_2 and $\omega = \mathfrak{e} \times \mathcal{R}_+$.

Examine the following two-variable nonlinear integral problem of the Volterra-Fredholm type.

$$\begin{aligned} &\varphi(\ddot{\mathfrak{t}},\ddot{\mathfrak{y}}) \\ &= \mathcal{A}\left(\ddot{\mathfrak{t}},\ddot{\mathfrak{y}},\varphi(\ddot{\mathfrak{t}},\ddot{\mathfrak{y}})\right) \\ &+ \int_0^{\ddot{\mathfrak{y}}} \int_{\mathfrak{e}} \mathcal{B}\left(\ddot{\mathfrak{t}},\ddot{\mathfrak{y}},\ddot{\imath},\mathfrak{b},\varphi(\ddot{\imath},\mathfrak{b}),(\Gamma\varphi)(\ddot{\imath},\mathfrak{b})\right) d\mathfrak{b}d\ddot{\imath}, \end{aligned} \tag{3}$$

for all $(\ddot{\mathfrak{t}},\ddot{\mathfrak{y}}) \in \omega$ where

$$\begin{aligned} &(\Gamma\varphi)(\ddot{\mathfrak{t}},\ddot{\mathfrak{y}}) \\ &= \int_0^{\ddot{\mathfrak{y}}} \int_{\mathfrak{e}} \mathcal{H}\left(\ddot{\mathfrak{t}},\ddot{\mathfrak{y}},\ddot{z},\ddot{\zeta},\varphi(\ddot{z},\ddot{\zeta})\right) d\ddot{\zeta}d\ddot{z}, \end{aligned} \tag{4}$$

and $\mathcal{A} \in C(\omega \times \mathcal{R},\mathcal{R})$, $\mathcal{B} \in C(\omega^2 \times \mathcal{R}^2,\mathcal{R})$, $\mathcal{H} \in C(\omega^2 \times \mathcal{R},\mathcal{R})$.

In this paper, we will demonstrate the presence and uniqueness of the Volterra-Fredholm integral equation solution in two variables. Using Banach's contraction principle, we investigate the existence and uniqueness of a solution to the Volterra-Fredholm integral problem. Additionally, a number of the solution's characteristics are identified.

Let $\mathcal{Z}$ denote the space of functions that satisfy the constraint $\ddot{\Phi} \in C(\omega,\mathcal{R})$.

$$\left|\ddot{\Phi}(\ddot{\mathfrak{t}},\ddot{\mathfrak{y}})\right| = \mathrm{O}\left(exp\left(\mathfrak{z}(\ddot{\mathfrak{t}} + |\ddot{\mathfrak{y}}|)\right)\right) \tag{5}$$

where a constant is $\mathfrak{z} > 0$. We define the norm "The norms ||v|| of a vector v and ||A|| of a matrix A are nonnegative real numbers that measure the size of v and A. In the case of a vector, norms are generalizations of the Euclidean lengths of vectors" in space $\mathcal{Z}$.

$$\left|\ddot{\Phi}\right|_z = \sup_{(\ddot{\mathfrak{t}},\ddot{\mathfrak{y}})\in\omega} \left[\left|\ddot{\Phi}\left(\ddot{\mathfrak{t}},\ddot{\mathfrak{y}}\right)\right| exp\left(-\mathfrak{z}(\ddot{\mathfrak{t}} + |\ddot{\mathfrak{y}}|)\right)\right]. \tag{6}$$

It is easy to see that $\mathcal{Z}$ is a Banach space when the norm specified in (2.4 is used. And

$$|\ddot{\Phi}|_z \leq \mathcal{M} \tag{7}$$

where a constant is $\mathcal{M} \geq 0$. Presenting some qualitative elements of (3) solutions discovered in [12], [13] ,is the primary goal of this part.

The existence and uniqueness of the solution to problem (3) are established using the Banach fixed-point theorem.

Theorem 1. Assume that

1) (3) are functions $\mathcal{A}$, $\mathcal{B}$, and $\mathcal{H}$ meet the requirements.

$$\left|\mathcal{A}(\ddot{\mathfrak{t}},\ddot{\mathfrak{y}},\varphi) - \mathcal{A}(\ddot{\mathfrak{t}},\ddot{\mathfrak{y}},\ddot{v})\right| \leq \mathcal{g}(\ddot{\mathfrak{t}},\ddot{\mathfrak{y}})|\varphi - \ddot{v}|, \tag{8}$$

$$\begin{aligned}&\left|\mathcal{B}(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathfrak{b},\varphi,\bar{\varphi})-\mathcal{B}(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathfrak{b},\ddot{v},\bar{\ddot{v}})\right|\\&\qquad\le r(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathfrak{b})[|\varphi-\ddot{v}|\\&\qquad+|\bar{\varphi}-\bar{\ddot{v}}|]\end{aligned}\tag{9}$$

And

$$\begin{aligned}&\left|\mathcal{H}(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{z},\ddot{\zeta},\varphi)-\mathcal{H}(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{z},\ddot{\zeta},\ddot{v})\right|\\&\qquad\le m(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{z},\ddot{\zeta})|\varphi-\ddot{v}|\end{aligned}\tag{10}$$

where $g\in C(\omega,\mathcal{R}_+)$ and $r,m\in C(\omega^2,\mathcal{R}_+)$

2) for λ as in (5);
3) there exists a nonnegative constant $\alpha<1$ such that:

$$\begin{aligned}&g(\ddot{\dagger},\ddot{\mathrm{q}})e^{\lambda(\ddot{\dagger}+|\ddot{\mathrm{q}}|)}\\&+\int_0^{\ddot{\mathrm{q}}}\int_{\mathrm{e}} r(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathfrak{b})\left[e^{\lambda(\ddot{\imath}+|\mathfrak{b}|)}\right.\\&\left.+\int_0^{\ddot{\mathrm{q}}}\int_{\mathrm{e}} m(\ddot{\imath},\mathfrak{b},\ddot{z},\ddot{\zeta})e^{\lambda(\ddot{z}+|\ddot{\zeta}|)}\,d\ddot{\zeta}d\ddot{z}\right]d\mathfrak{b}d\ddot{\imath}\\&\le\alpha e^{\lambda(\ddot{\dagger}+|\ddot{\mathrm{q}}|)}\end{aligned}\tag{11}$$

4) A nonnegative constant β exists such that

$$\begin{aligned}&|\mathcal{A}(\ddot{\dagger},\ddot{\mathrm{q}},0)|\\&+\int_0^{\ddot{\mathrm{q}}}\int_{\mathrm{e}}\left|\mathcal{B}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathfrak{b},0,(\Gamma 0)(\ddot{\imath},\mathfrak{b})\right)\right|d\mathfrak{b}d\ddot{\imath}\\&\le\beta e^{\lambda(\ddot{\dagger}+|\ddot{\mathrm{q}}|)}\end{aligned}\tag{12}$$

where $\mathcal{A},\mathcal{B}$ are as defined in (3). Then, $\varphi(\ddot{\dagger},\ddot{\mathrm{q}})\ in\ \omega\ on\ \mathcal{Z}$ is the only solution to (3).

$proof.$ Define the operator Ψ by letting $\varphi\in\mathcal{Z}$.

$$\begin{aligned}&(\Psi\varphi)(\ddot{\dagger},\ddot{\mathrm{q}})\\&=\mathcal{A}\left(\ddot{\dagger},\ddot{\mathrm{q}},\varphi(\ddot{\dagger},\ddot{\mathrm{q}})\right)\\&+\int_0^{\ddot{\mathrm{q}}}\int_{\mathrm{e}}\mathcal{B}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathfrak{b},\varphi(\ddot{\imath},\mathfrak{b}),(\Gamma\varphi)(\ddot{\imath},\mathfrak{b})\right)d\mathfrak{b}d\ddot{\imath}\end{aligned}\tag{13}$$

for all $(\ddot{\dagger},\ddot{\mathrm{q}})\in\omega$

To prove the theorem, from (13) and applying the theories, we have

$$\begin{aligned}&\left|(\Psi\varphi)(\ddot{\dagger},\ddot{\mathrm{q}})\right|\\&\le\left|\mathcal{A}\left(\ddot{\dagger},\ddot{\mathrm{q}},\varphi(\ddot{\dagger},\ddot{\mathrm{q}})\right)\right|\\&+\int_0^{\ddot{\mathrm{q}}}\int_{\mathrm{e}}\left|\mathcal{B}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathfrak{b},\varphi(\ddot{\imath},\mathfrak{b}),(\Gamma\varphi)(\ddot{\imath},\mathfrak{b})\right)\right|d\mathfrak{b}d\ddot{\imath}\end{aligned}\tag{14}$$

$$\begin{aligned}&\le\left|\mathcal{A}\left(\ddot{\dagger},\ddot{\mathrm{q}},\varphi(\ddot{\dagger},\ddot{\mathrm{q}})\right)-\mathcal{A}(\ddot{\dagger},\ddot{\mathrm{q}},0)+\mathcal{A}(\ddot{\dagger},\ddot{\mathrm{q}},0)\right|\\&+\int_0^{\ddot{\mathrm{q}}}\int_{\mathrm{e}}\left\{\left|\mathcal{B}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathfrak{b},\varphi(\ddot{\imath},\mathfrak{b}),\right.\right.\right.\\&\left[\int_0^{\ddot{\mathrm{q}}}\int_{\mathrm{e}}\left|\mathcal{H}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{z},\ddot{\zeta},\varphi(\ddot{z},\ddot{\zeta})\right)-\mathcal{H}(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{z},\ddot{\zeta},0)\right.\right.\\&\left.\left.+\mathcal{H}(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{z},\ddot{\zeta},0)\right|d\ddot{\zeta}d\ddot{z}]\Big)\\&-\mathcal{B}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathfrak{b},0,(\Gamma 0)(\ddot{\imath},\mathfrak{b})\right)\\&\left.\left.+\mathcal{B}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathfrak{b},0,(\Gamma 0)(\ddot{\imath},\mathfrak{b})\right)\right|\right\}d\mathfrak{b}d\ddot{\imath}\\&\le|\mathcal{A}(\ddot{\dagger},\ddot{\mathrm{q}},0)|\\&+\int_0^{\ddot{\mathrm{q}}}\int_{\mathrm{e}}\left|\mathcal{B}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathfrak{b},0,(\Gamma 0)(\ddot{\imath},\mathfrak{b})\right)\right|d\mathfrak{b}d\ddot{\imath}\\&+g(\ddot{\dagger},\ddot{\mathrm{q}})|\varphi|\\&\quad+\int_0^{\ddot{\mathrm{q}}}\int_{\mathrm{e}}\left\{r(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathfrak{b})[|\varphi|+|\bar{\varphi}|]\right.\\&\quad\left.+\left[\int_0^{\mathfrak{b}}\int_{\mathrm{e}} m(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{z},\ddot{\zeta})|\varphi|d\ddot{\zeta}d\ddot{z}\right]\right\}d\mathfrak{b}d\ddot{\imath}\\&\le\beta e^{\lambda(\ddot{\dagger}+|\ddot{\mathrm{q}}|)}\\&+|\varphi|_z\left[g(\ddot{\dagger},\ddot{\mathrm{q}})e^{\lambda(\ddot{\dagger}+|\ddot{\mathrm{q}}|)}\right.\\&+\int_0^{\ddot{\mathrm{q}}}\int_{\mathrm{e}} r(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathfrak{b})\left(e^{\lambda(\ddot{\imath}+|\mathfrak{b}|)}\right.\\&\left.\left.+\int_0^{\ddot{\mathrm{q}}}\int_{\mathrm{e}} m(\ddot{\imath},\mathfrak{b},\ddot{z},\ddot{\zeta})e^{\lambda(\ddot{z}+|\ddot{\zeta}|)}\,d\ddot{\zeta}d\ddot{z}\right)d\mathfrak{b}d\ddot{\imath}\right]\\&\le\beta e^{\lambda(\ddot{\dagger}+|\ddot{\mathrm{q}}|)}+|\varphi|_z\alpha e^{\lambda(\ddot{\dagger}+|\ddot{\mathrm{q}}|)}\\&\le\beta e^{\lambda(\ddot{\dagger}+|\ddot{\mathrm{q}}|)}+\mathcal{M}\alpha e^{\lambda(\ddot{\dagger}+|\ddot{\mathrm{q}}|)}\\&|(\Psi\varphi)(\ddot{\dagger},\ddot{\mathrm{q}})|\le[\beta+\mathcal{M}\alpha]e^{\lambda(\ddot{\dagger}+|\ddot{\mathrm{q}}|)}\end{aligned}$$

$$\left|(\Psi\varphi)(\ddot{\dagger},\ddot{\mathrm{q}})\right|_z\le[\beta+\mathcal{M}\alpha]\tag{16}$$

From (16), Consequently $\Psi\varphi\in\mathcal{Z}$. Let $\varphi,\ \ddot{v}\in\mathcal{Z}$. From (13) and applying the theories, we have

$$\begin{aligned}&\left|(\Psi\varphi)(\ddot{\dagger},\ddot{\mathrm{q}})-(\Psi\ddot{v})(\ddot{\dagger},\ddot{\mathrm{q}})\right|\\&\le\left|\mathcal{A}\left(\ddot{\dagger},\ddot{\mathrm{q}},\varphi(\ddot{\dagger},\ddot{\mathrm{q}})\right)-\mathcal{A}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{v}(\ddot{\dagger},\ddot{\mathrm{q}})\right)\right|\\&+\int_0^{\ddot{\mathrm{q}}}\int_{\mathrm{e}}\{|\mathcal{B}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathfrak{b},\varphi(\ddot{\imath},\mathfrak{b}),\right.\\&\left[\int_0^{\mathfrak{b}}\int_{\mathrm{e}}\left|\mathcal{H}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{z},\ddot{\zeta},\varphi(\ddot{z},\ddot{\zeta})\right)\right|d\ddot{\zeta}d\ddot{z}\right]\Big)\\&-\mathcal{B}(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathfrak{b},\ddot{v}(\ddot{\imath},\mathfrak{b}),\\&\left.\left.\left[\int_0^{\mathfrak{b}}\int_{\mathrm{e}}\left|\mathcal{H}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{z},\ddot{\zeta},\ddot{v}(\ddot{z},\ddot{\zeta})\right)\right|d\ddot{\zeta}d\ddot{z}\right]\right)\right|\right\}d\mathfrak{b}d\ddot{\imath}\\&\le g(\ddot{\dagger},\ddot{\mathrm{q}})|\varphi-\ddot{v}|\end{aligned}$$

$$+\int_0^{\ddot{\imath}}\int_{\mathrm{e}}\left\{r(\ddot{\dagger},\ddot{\imath},\ddot{\imath},\mathcal{B})[|\,\varphi-\ddot{v}|+|\overline{\varphi}-\bar{\bar{v}}|]\right.$$
$$\left.+\left[\int_0^{\mathcal{B}}\int_{\mathrm{e}} m(\ddot{\imath},\mathcal{B},\ddot{z},\ddot{\zeta})|\,\varphi-\ddot{v}|d\ddot{\zeta}d\ddot{z}\right]\right\}d\mathcal{B}d\ddot{\imath}$$
$$\leq|\,\varphi-\ddot{v}|_z\left[g(\ddot{\dagger},\ddot{\imath})e^{\lambda(\ddot{\dagger}+|\ddot{\imath}|)}\right.$$
$$+\int_0^{\ddot{\imath}}\int_{\mathrm{e}} r(\ddot{\dagger},\ddot{\imath},\ddot{\imath},\mathcal{B})\left(e^{\lambda(\ddot{\imath}+|\mathcal{B}|)}\right.$$
$$\left.\left.+\int_0^{\mathcal{B}}\int_{\mathrm{e}} m(\ddot{\imath},\mathcal{B},\ddot{z},\ddot{\zeta})e^{\lambda(\ddot{z}+|\ddot{\zeta}|)}\,d\ddot{\zeta}d\ddot{z}\right)d\mathcal{B}d\ddot{\imath}\right]$$

$$|\Psi\,\varphi)(\ddot{\dagger},\ddot{\imath})-(\Psi\ddot{v})(\ddot{\dagger},\ddot{\imath})|\leq|\,\varphi-\ddot{v}|_z\alpha e^{\lambda(\ddot{\dagger}+|\ddot{\imath}|)}$$
$$|\Psi\,\varphi-\Psi\ddot{v}|_z\leq|\,\varphi-\ddot{v}|_z\alpha$$

According to the Banach fixed point theorem see [14], [15], Ψ has a unique fixed point in Z. Since α < 1. (13) has a solution at the fixed point of Ψ. This evidence is comprehensive.

4 CHARACTERISTICS OF SOLUTIONS

In this section, we examine some fundamental characteristics of the solutions to (3) using the inequality established in [12] and Theorem 1.

First, we will provide the subsequent theorem regarding the estimate of the solution to (3).

Theorem 2. Assume that the functions $\mathcal{A}$, $\mathcal{B}$ and $\mathcal{H}$ in (3) and (4)" satisfy the requirements.

$$|\mathcal{A}(\ddot{\dagger},\ddot{\imath},\varphi)-\mathcal{A}(\ddot{\dagger},\ddot{\imath},\ddot{v})|\leq g(\ddot{\dagger},\ddot{\imath})|\varphi-\ddot{v}| \tag{17}$$

$$|\mathcal{B}(\ddot{\dagger},\ddot{\imath},\ddot{\imath},\mathcal{B},\varphi,\overline{\varphi})-\mathcal{B}(\ddot{\dagger},\ddot{\imath},\ddot{\imath},\mathcal{B},\ddot{v},\bar{\bar{v}})|$$
$$\leq q(\ddot{\dagger},\ddot{\imath})p(\ddot{\imath},\mathcal{B})[|\varphi-\ddot{v}|+|\overline{\varphi}-\bar{\bar{v}}|] \tag{18}$$

$$|\mathcal{H}(\ddot{\dagger},\ddot{\imath},\ddot{z},\ddot{\zeta},\varphi)-\mathcal{H}(\ddot{\dagger},\ddot{\imath},\ddot{z},\ddot{\zeta},\ddot{v})|$$
$$\leq q(\ddot{\dagger},\ddot{\imath})n(\ddot{z},\ddot{\zeta})|\varphi-\ddot{v}| \tag{19}$$

where $g,q,p,n\in C(\omega,\mathcal{R}_+)$, Let

$$c=\sup_{(\ddot{\dagger},\ddot{\imath})\in\omega}\left|\mathcal{A}(\ddot{\dagger},\ddot{\imath},0)\right.$$
$$\left.+\int_0^{\ddot{\imath}}\int_{\mathrm{e}}\mathcal{B}\left(\ddot{\dagger},\ddot{\imath},\ddot{\imath},\mathcal{B},0,(\Gamma 0)(\ddot{\imath},\mathcal{B})\right)d\mathcal{B}d\ddot{\imath}\right| \tag{20}$$

If φ $(\ddot{\dagger}$ $\ddot{\imath})$ is any solution of (3) on ω, then

$$|\varphi(\ddot{\dagger},\ddot{\imath})|\leq c[g(\ddot{\dagger},\ddot{\imath})+q(\ddot{\dagger},\ddot{\imath})\int_0^{\ddot{\imath}}\int_{\mathrm{e}}[p(\ddot{\imath},\mathcal{B})$$
$$+n(\ddot{\imath},\mathcal{B})]\times exp\left(\int_0^{\ddot{\imath}}\int_{\mathrm{e}} q(\ddot{z},\ddot{\zeta})[f(\ddot{z},\ddot{\zeta})\right.$$
$$\left.+n(\ddot{z},\ddot{\zeta})]d\ddot{\zeta}d\ddot{z}\right)d\mathcal{B}d\ddot{\imath}\Big] \tag{21}$$

for all $(\ddot{\dagger},\ddot{\imath})\in\omega$

Proof. Using the hypotheses and given that (3) can be solved by $\varphi(\ddot{\dagger},\ddot{\imath})$, we have

$$|\varphi(\ddot{\dagger},\ddot{\imath})|$$
$$\leq\left|\mathcal{A}\left(\ddot{\dagger},\ddot{\imath},\varphi(\ddot{\dagger},\ddot{\imath})\right)-\mathcal{A}(\ddot{\dagger},\ddot{\imath},0)+\mathcal{A}(\ddot{\dagger},\ddot{\imath},0)\right|$$
$$+\int_0^{\ddot{\imath}}\int_{\mathrm{e}}\left\{\left|\mathcal{B}\left(\ddot{\dagger},\ddot{\imath},\ddot{\imath},\mathcal{B},\varphi(\ddot{\dagger},\ddot{\imath}),\right.\right.\right.$$
$$\left[\int_0^{\mathcal{B}}\int_{\mathrm{e}}\left|\mathcal{H}\left(\ddot{\dagger},\ddot{\imath},\ddot{z},\ddot{\zeta},\varphi(\ddot{z},\ddot{\zeta})\right)-\mathcal{H}(\ddot{\dagger},\ddot{\imath},\ddot{z},\ddot{\zeta},0)\right.\right.$$
$$\left.\left.+\mathcal{H}(\ddot{\dagger},\ddot{\imath},\ddot{z},\ddot{\zeta},0)\right|d\ddot{\zeta}d\ddot{z}\right]\Big)$$
$$-\mathcal{B}\left(\ddot{\dagger},\ddot{\imath},\ddot{\imath},\mathcal{B},0,(\Gamma 0)(\ddot{\imath},\mathcal{B})\right)$$
$$\left.\left.+\mathcal{B}\left(\ddot{\dagger},\ddot{\imath},\ddot{\imath},\mathcal{B},0,(\Gamma 0)(\ddot{\imath},\mathcal{B})\right)\right|\right\}d\mathcal{B}d\ddot{\imath}$$
$$\leq\Big|\mathcal{A}(\ddot{\dagger},\ddot{\imath},0)$$
$$+\int_0^{\ddot{\imath}}\int_{\mathrm{e}}+\mathcal{B}\left(\ddot{\dagger},\ddot{\imath},\ddot{\imath},\mathcal{B},0,(\Gamma 0)(\ddot{\imath},\mathcal{B})\right)d\mathcal{B}d\ddot{\imath}\Big|$$
$$+\left|\mathcal{A}\left(\ddot{\dagger},\ddot{\imath},\varphi(\ddot{\dagger},\ddot{\imath})\right)-\mathcal{A}(\ddot{\dagger},\ddot{\imath},0)\right|+$$

$$\int_0^{\ddot{\imath}}\int_{\mathrm{e}}\left\{\left|\mathcal{B}\left(\ddot{\dagger},\ddot{\imath},\ddot{\imath},\mathcal{B},\varphi(\ddot{\dagger},\ddot{\imath}),\right.\right.\right.$$
$$\left[\int_0^{\mathcal{B}}\int_{\mathrm{e}}\left|\mathcal{H}\left(\ddot{\dagger},\ddot{\imath},\ddot{z},\ddot{\zeta},\varphi(\ddot{z},\ddot{\zeta})\right)-\mathcal{H}(\ddot{\dagger},\ddot{\imath},\ddot{z},\ddot{\zeta},0)\right.\right.$$
$$\left.\left.+\mathcal{H}(\ddot{\dagger},\ddot{\imath},\ddot{z},\ddot{\zeta},0)\right|d\ddot{\zeta}d\ddot{z}\right]\Big)$$
$$\left.\left.-\mathcal{B}\left(\ddot{\dagger},\ddot{\imath},\ddot{\imath},\mathcal{B},0,(\Gamma 0)(\ddot{\imath},\mathcal{B})\right)\right|\right\}d\mathcal{B}d\ddot{\imath}$$
$$\leq c+g(\ddot{\dagger},\ddot{\imath})|\varphi(\ddot{\dagger},\ddot{\imath})|$$
$$+q(\ddot{\dagger},\ddot{\imath})\int_0^{\ddot{\imath}}\int_{\mathrm{e}}p(\ddot{\imath},\mathcal{B})\Big[|\varphi(\ddot{\imath},\mathcal{B})| \tag{22}$$
$$\left.+q(\ddot{\imath},\mathcal{B})\int_0^{\mathcal{B}}\int_{\mathrm{e}}n(\ddot{z},\ddot{\zeta})|\varphi(\ddot{z},\ddot{\zeta})|d\ddot{\zeta}d\ddot{z}\right]d\mathcal{B}d\ddot{\imath}.$$

We can observe from (22) and Theorem 1 in [12] that

$$|\varphi(\ddot{\dagger},\ddot{\imath})|\leq c[g(\ddot{\dagger},\ddot{\imath})$$
$$+q(\ddot{\dagger},\ddot{\imath})\int_0^{\ddot{\imath}}\int_{\mathrm{e}}[p(\ddot{\imath},\mathcal{B})+n(\ddot{\imath},\mathcal{B})]$$
$$\times exp\left(\int_0^{\ddot{\imath}}\int_{\mathrm{e}} q(\ddot{z},\ddot{\zeta})[f(\ddot{z},\ddot{\zeta})\right.$$
$$\left.+n(\ddot{z},\ddot{\zeta})]d\ddot{\zeta}d\ddot{z}\right)d\mathcal{B}d\ddot{\imath}\Big] \tag{23}$$

This proof is complete.

Lastly, we provide a result regarding the (3) solution's continuous dependency on the functions involved. Analyse (3) and its equivalent equation.

$$\begin{aligned}\ddot{v}(\ddot{\dagger},\ddot{\mathrm{q}}) &= \bar{\mathcal{A}}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{v}(\ddot{\dagger},\ddot{\mathrm{q}})\right)\\ &+\int_0^{\ddot{\mathrm{q}}}\int_{\mathrm{e}} \bar{\mathcal{B}}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathcal{B},\ddot{v}(\ddot{\imath},\mathcal{B}),(\bar{\Gamma}\ddot{v})(\ddot{\imath},\mathcal{B})\right)d\mathcal{B}d\ddot{\imath},\end{aligned} \tag{24}$$

for all $(\ddot{\dagger},\ddot{\mathrm{q}}) \in \omega$ where:

$$(\bar{\Gamma}\ddot{v})(\ddot{\dagger},\ddot{\mathrm{q}}) = \int_0^{\ddot{\mathrm{q}}}\int_{\mathrm{e}} \bar{\mathcal{H}}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{z},\ddot{\zeta},\ddot{v}(\ddot{z},\ddot{\zeta})\right)d\ddot{\zeta}d\ddot{z},$$

and $\bar{\mathcal{A}} \in C(\omega\times\mathcal{R},\mathcal{R})$, $\bar{\mathcal{B}} \in C(\omega^2\times\mathcal{R}^2,\mathcal{R})$, $\bar{\mathcal{H}} \in C(\omega^2\times\mathcal{R},\mathcal{R})$.

Theorem 3. Assume that, respectively, the functions $\mathcal{A}, \mathcal{B}$ *and* $\mathcal{H}$ in (3) fulfil the requirements (17), (18) and (19). Additionally, assume that the supplied solution to (23) on ω is $\ddot{v}(\ddot{\dagger},\ddot{\mathrm{q}})$.

$$\begin{aligned}&\left|\mathcal{A}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{v}(\ddot{\dagger},\ddot{\mathrm{q}})\right)-\bar{\mathcal{A}}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{v}(\ddot{\dagger},\ddot{\mathrm{q}})\right)\right|\\ &+\int_0^{\ddot{\mathrm{q}}}\int_{\mathrm{e}}\left|\mathcal{B}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathcal{B},\ddot{v}(\ddot{\imath},\mathcal{B}),(\Gamma\ddot{v})(\ddot{\imath},\mathcal{B})\right)\right.\\ &\left.-\bar{\mathcal{B}}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathcal{B},\ddot{v}(\ddot{\imath},\mathcal{B}),(\bar{\Gamma}\ddot{v})(\ddot{\imath},\mathcal{B})\right)\right|d\mathcal{B}d\ddot{\imath}\le\varepsilon,\end{aligned}$$

where $\mathrm{A},\mathrm{B},\Gamma\varphi$ and $\bar{\mathrm{A}},\bar{\mathrm{B}},\bar{\Gamma}\ddot{v}$ are as in (3) and (23) and ε > 0 is a small, arbitrary constant, respectively. Then, the functions involved in (3) determine the solution $\varphi(\ddot{\dagger},\ddot{\mathrm{q}})$ of (3) on ω continuously.

Proof. Let $\mathcal{D}(\ddot{\dagger},\ddot{\mathrm{q}}) = \left|\varphi(\ddot{\dagger},\ddot{\mathrm{q}})-\ddot{v}(\ddot{\dagger},\ddot{\mathrm{q}})\right|$, for $(\ddot{\dagger},\ddot{\mathrm{q}}) \in \omega$. Using the hypotheses, we have:

$$\begin{aligned}\mathcal{D}(\ddot{\dagger},\ddot{\mathrm{q}}) &\le \left|\mathcal{A}\left(\ddot{\dagger},\ddot{\mathrm{q}},\varphi(\ddot{\dagger},\ddot{\mathrm{q}})\right)\right.\\ &\qquad\left.-\mathcal{A}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{v}(\ddot{\dagger},\ddot{\mathrm{q}})\right)\right|\\ &+\left|\mathcal{A}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{v}(\ddot{\dagger},\ddot{\mathrm{q}})\right)-\bar{\mathcal{A}}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{v}(\ddot{\dagger},\ddot{\mathrm{q}})\right)\right|\\ &+\int_0^{\ddot{\mathrm{q}}}\int_{\mathrm{e}}\left|\mathcal{B}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathcal{B},\varphi(\ddot{\imath},\mathcal{B}),(\Gamma\varphi)(\ddot{\imath},\mathcal{B})\right)\right.\\ &\left.-\mathcal{B}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathcal{B},\ddot{v}(\ddot{\imath},\mathcal{B}),(\Gamma\ddot{v})(\ddot{\imath},\mathcal{B})\right)\right|d\mathcal{B}d\ddot{\imath}\\ &+\int_0^{\ddot{\mathrm{q}}}\int_{\mathrm{e}}\left|\mathcal{B}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathcal{B},\ddot{v}(\ddot{\imath},\mathcal{B}),(\Gamma\ddot{v})(\ddot{\imath},\mathcal{B})\right)\right.\\ &\left.-\bar{\mathcal{B}}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathcal{B},\ddot{v}(\ddot{\imath},\mathcal{B}),(\bar{\Gamma}\ddot{v})(\ddot{\imath},\mathcal{B})\right)\right|d\mathcal{B}d\ddot{\imath}\\ &\le\varepsilon+\mathcal{g}(\ddot{\dagger},\ddot{\mathrm{q}})\mathcal{D}(\ddot{\dagger},\ddot{\mathrm{q}})\\ &+\mathcal{q}(\ddot{\dagger},\ddot{\mathrm{q}})\int_0^{\ddot{\mathrm{q}}}\int_{\mathrm{e}}\mathcal{p}(\ddot{\imath},\mathcal{B})\left[\mathcal{D}(\ddot{\imath},\mathcal{B})\right.\\ &\left.+\mathcal{q}(\ddot{\imath},\mathcal{B})\int_0^{\mathcal{B}}\int_{\mathrm{e}}\mathcal{n}(\ddot{z},\ddot{\zeta})\mathcal{D}(\ddot{z},\ddot{\zeta})d\ddot{\zeta}d\ddot{z}\right]d\mathcal{B}d\ddot{\imath}\end{aligned} \tag{26}$$

Now, applying [6] Theorem 1, the relation (26) produces:

$$\begin{aligned}&\left|\varphi(\ddot{\dagger},\ddot{\mathrm{q}})-\ddot{v}(\ddot{\dagger},\ddot{\mathrm{q}})\right| \le \varepsilon\left[\mathcal{g}(\ddot{\dagger},\ddot{\mathrm{q}})\right.\\ &\left.+\mathcal{q}(\ddot{\dagger},\ddot{\mathrm{q}})\int_0^{\ddot{\mathrm{q}}}\int_{\mathrm{e}}\left[\mathcal{p}(\ddot{\imath},\mathcal{B})+\mathcal{n}(\ddot{\imath},\mathcal{B})\right]\right.\\ &\left.\times exp\left(\int_0^{\ddot{\mathrm{q}}}\int_{\mathrm{e}}\mathcal{q}(\ddot{z},\ddot{\zeta})\left[\mathcal{p}(\ddot{z},\ddot{\zeta})+\mathcal{n}(\ddot{z},\ddot{\zeta})\right]d\ddot{\zeta}d\ddot{z}\right)d\mathcal{B}d\ddot{\imath}\right]\end{aligned} \tag{27}$$

For $(\ddot{\dagger},\ddot{\mathrm{q}}) \in \omega$. From (27) Consequently, the functions involved in (3) determine the answer in a continuous manner.

This proof is complete.

5 AN EXAMPLE

The problem under consideration is described by the following nonlinear Volterra–Fredholm integral equation:

$$\begin{aligned}\varphi(\ddot{\dagger},\ddot{\mathrm{q}}) &= w(\ddot{\dagger},\ddot{\mathrm{q}})\varphi(\ddot{\dagger},\ddot{\mathrm{q}})\\ &+\int_0^{\ddot{\mathrm{q}}}\int_{\mathrm{e}}\left(d(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathcal{B})\varphi(\ddot{\imath},\mathcal{B})\right.\\ &\left.+\int_0^{\ddot{z}}\int_{\mathrm{e}} f(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{z},\ddot{\zeta})\varphi(\ddot{z},\ddot{\zeta})d\ddot{\zeta}d\ddot{z}\right)d\mathcal{B}d\ddot{\imath}\end{aligned} \tag{28}$$

where $w(\ddot{\dagger},\ddot{\mathrm{q}}) = \frac{\lambda}{13}e^{\lambda(\ddot{\dagger}+|\ddot{\mathrm{q}}|)}$

$$d(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathcal{B}) = \frac{\lambda^2}{e^{\lambda}-1}e^{\lambda(\ddot{\dagger}+|\ddot{\mathrm{q}}|)}$$

$$f(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{z},\ddot{\zeta}) = \frac{\lambda^2}{t(e^{\lambda}-1)}e^{\lambda(\ddot{\dagger}+|\ddot{\mathrm{q}}|)}$$

$\mathrm{e} = [0,1]$, $\lambda > 0$ Here,

$$\mathcal{A}\left(\ddot{\dagger},\ddot{\mathrm{q}},\varphi(\ddot{\dagger},\ddot{\mathrm{q}})\right) = w(\ddot{\dagger},\ddot{\mathrm{q}})\varphi(\ddot{\dagger},\ddot{\mathrm{q}})$$

$$\mathcal{H}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{z},\ddot{\zeta},\varphi(\ddot{z},\ddot{\zeta})\right) = \int_0^{\ddot{z}}\int_0^{1} f(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{z},\ddot{\zeta})\varphi(\ddot{z},\ddot{\zeta})d\ddot{\zeta}d\ddot{z}$$

$$\mathcal{B}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathcal{B},\varphi(\ddot{\imath},\mathcal{B}),(\Gamma\varphi)(\ddot{\imath},\mathcal{B})\right) = \int_0^{\ddot{\mathrm{q}}}\int_0^{1}\left(d(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathcal{B})\varphi(\ddot{\imath},\mathcal{B})+(\Gamma\varphi)(\ddot{\imath},\mathcal{B})\right)d\mathcal{B}d\ddot{\imath}$$

We can see that

$$\left|\mathcal{A}(\ddot{\dagger},\ddot{\mathrm{q}},\varphi)-\mathcal{A}(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{v})\right| \le \frac{\lambda}{13}e^{\lambda(\ddot{\dagger}+|\ddot{\mathrm{q}}|)}|\varphi-\ddot{v}|$$

$$\left|\mathcal{H}(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{z},\ddot{\zeta},\varphi)-\mathcal{H}(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{z},\ddot{\zeta},\ddot{v})\right| \le \frac{\lambda^2}{e^{\lambda}-1}e^{\lambda(\ddot{\dagger}+|\ddot{\mathrm{q}}|)}|\varphi-\ddot{v}|$$

$$\left|\mathcal{B}(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathcal{B},\varphi,\bar{\varphi})-\mathcal{B}(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathcal{B},\ddot{v},\bar{\ddot{v}})\right| \le \frac{2\lambda^2}{e^{\lambda}-1}e^{\lambda(\ddot{\dagger}+|\ddot{\mathrm{q}}|)}|\varphi-\ddot{v}|.$$

By choosing $r(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathcal{B}) = \frac{2\lambda^2}{e^{\lambda}-1}e^{\lambda(\ddot{\dagger}+|\ddot{\mathrm{q}}|)}$ and $m(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{z},\ddot{\zeta}) = \frac{\lambda^2}{e^{\lambda}-1}e^{\lambda(\ddot{\dagger}+|\ddot{\mathrm{q}}|)}$

It is easy to see that the functions $r(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathcal{B})$ and $m(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{z},\ddot{\zeta})$ are continuous, and so the conditions (1)-(2) are satisfied on the order hand, we get that:

$$|\mathcal{A}(\ddot{\dagger},\ddot{\mathrm{q}},0)| + \int_0^{\ddot{\mathrm{q}}}\int_{\mathrm{e}} \left|\mathcal{B}\left(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathfrak{b},0,(\Gamma 0)(\ddot{\imath},\mathfrak{b})\right)\right| d\mathfrak{b}d\ddot{\imath} \leq \beta e^{\lambda(|\ddot{\dagger}|+|\ddot{\mathrm{q}}|)}$$

$$\frac{\lambda}{13} e^{\lambda(|\ddot{\dagger}|+|\ddot{\mathrm{q}}|)} \leq \beta e^{\lambda(|\ddot{\dagger}|+|\ddot{\mathrm{q}}|)}$$

Which satisfied the condition (4) of Theorem 1 with $\beta = \frac{\lambda}{13}$ and $\lambda > 0$. Moreover:

$$g(\ddot{\dagger},\ddot{\mathrm{q}})e^{\lambda(|\ddot{\dagger}|+|\ddot{\mathrm{q}}|)} + \int_0^{\ddot{\mathrm{q}}}\int_{\mathrm{e}} r(\ddot{\dagger},\ddot{\mathrm{q}},\ddot{\imath},\mathfrak{b}) \left[e^{\lambda(|\ddot{\imath}|+|\mathfrak{b}|)} + \int_0^{\ddot{\mathrm{q}}}\int_{\mathrm{e}} m(\ddot{\imath},\mathfrak{b},\ddot{z},\ddot{\zeta})e^{\lambda(|\ddot{z}|+|\ddot{\zeta}|)}\, d\ddot{\zeta}d\ddot{z}\right] d\mathfrak{b}d\ddot{\imath} \leq \alpha e^{\lambda(|\ddot{\dagger}|+|\ddot{\mathrm{q}}|)}$$

$$\Rightarrow \frac{\lambda}{13} e^{\lambda(|\ddot{\dagger}|+|\ddot{\mathrm{q}}|)} + \frac{2\lambda^2}{e^{\lambda}-1} e^{\lambda(|\ddot{\dagger}|+|\ddot{\mathrm{q}}|)} \int_0^{\ddot{\mathrm{q}}}\int_0^1 \left[e^{\lambda(|\ddot{\imath}|+|\mathfrak{b}|)} + \frac{\lambda^2}{e^{\lambda}-1} e^{\lambda(|\ddot{\imath}|+|\mathfrak{b}|)} \int_0^{\ddot{z}}\int_0^1 e^{\lambda(|\ddot{z}|+|\ddot{\zeta}|)}\, d\ddot{\zeta}d\ddot{z}\right] d\mathfrak{b}d\ddot{\imath} \leq \alpha e^{\lambda(|\ddot{\dagger}|+|\ddot{\mathrm{q}}|)}$$

$$\Rightarrow \frac{\lambda}{13} e^{\lambda(|\ddot{\dagger}|+|\ddot{\mathrm{q}}|)} + (e^{\lambda}+1)(e^{\lambda\ddot{\mathrm{q}}}-1)e^{\lambda(|\ddot{\dagger}|+|\ddot{\mathrm{q}}|)} \leq \alpha e^{\lambda(|\ddot{\dagger}|+|\ddot{\mathrm{q}}|)}$$

$$\left[\frac{\lambda}{13} + (e^{\lambda}+1)(e^{\lambda\ddot{\mathrm{q}}}-1)\right] e^{\lambda(|\ddot{\dagger}|+|\ddot{\mathrm{q}}|)} \leq \alpha e^{\lambda(|\ddot{\dagger}|+|\ddot{\mathrm{q}}|)}$$

If we chose $\ddot{\mathrm{q}} = ln\left(\frac{e^{\lambda}+2}{e^{\lambda}+1}\right)^{\frac{1}{\lambda}}, \lambda > 0$

$$\alpha = \frac{\lambda}{13} + (e^{\lambda}+1)(e^{\lambda\ddot{\mathrm{q}}}-1) < 1$$

It follows that the condition (3) of Theorem 1 is satisfied for $\alpha < 1$.

From the results above, we infer that the problem (28) satisfied the all conditions of Theorem 1, which guarantees the problem (28) has a unique solution.

6 CONCLUSIONS

The existence and uniqueness of solutions for the nonlinear Volterra-Fredholm integral equation in two variables have been rigorously established through the application of the Banach contraction principle and the imposition of Lipschitz conditions within a Banach space. The qualitative properties of these solutions have been thoroughly analyzed using specific integral inequalities, providing a comprehensive understanding of their fundamental behavior and structural characteristics. Furthermore, the solutions exhibit continuous dependence on the governing functions and parameters, demonstrating the stability of the model under small perturbations and ensuring its robustness for practical applications. Illustrative examples confirm the mathematical consistency and effectiveness of the proposed framework, highlighting its potential for extension to a broader class of multidimensional nonlinear integral equations and its applicability in complex mathematical modeling scenarios.

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Digital Image Inpainting Analysis Based on the Cahn-Hilliard Model

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Abstract: One of the most important applications in image processing is digital image restoration, which attempts to restore sections of an image that have been lost or damaged. In this paper, we analyze and implement the Cahn-Hilliard model, a fourth-order nonlinear partial differential equation renowned for its efficiency and speed in preserving structural continuity and smoothness in the image. The model is designed to restore regions affected by intentional damage, scratches, or distortions. The model was numerically solved using the implicit finite difference method, which produced a stable and precise reconstruction using the convex partitioning technique. We applied the model to images with deliberate defects within eight different color spaces, including YUV, YCbCr, RGB, NTSC, XYZ, HSV, and others, and evaluated its performance in terms of restoration accuracy and the absence of visual distortions. The effectiveness of the Cahn-Hilliard model outperforms traditional restoration methods in reconstructing missing areas while preserving the original edges and fine details.

1 INTRODUCTION

A fundamental problem in digital image processing is the reconstruction of absent or impaired areas within an image by utilizing information derived from adjacent pixels. This technique, known as inpainting, serves as a specific type of interpolation. Furthermore, it facilitates the restoration of compromised photographs impacted by elements like aging, scratches, deterioration, or deliberate harm. Furthermore, inpainting can facilitate the recoloring of occluded objects by recreating the concealed information utilizing contextual clues [1]. Bretozzi was the pioneer in presenting a two-scale analytical model derived from the Cahn-Hilliard equation, which has demonstrated efficacy in the processing of binary images, especially those consisting solely of two hues (black and white). The Cahn-Hilliard framework, initially developed as a physical and mathematical model, has been effectively modified for image processing applications, particularly image inpainting, owing to its superior efficiency and rapidity in managing high-contrast images [2] - [4]. Bertozzi further advanced an extended model, known as the Bertozzi-Esedoglu-Gillette Cahn-Hilliard model, to accommodate images with n channels. Bertozzi and her partners specifically created a fidelity term to guarantee that the inpainted image closely resembles the original before purposeful damage or noise. The extended model exhibits robust mathematical and numerical performance; yet, it encounters a critical issue: the compromise of mass conservation, which pertains to maintaining the spatial average of the phase field [5]. Researchers continue to strive to address this constraint, particularly in ensuring mass conservation when incorporating the fidelity term. A recent study by Nils Boulerion proposed optimal control strategies for the fidelity parameter that balance inpainting accuracy and mass preservation [6], [7]. The study conducted by Bretozzi, Cecilia, Matteo, and M. Grasselli focuses on an image inpainting model that was initially presented by A. Bretozzi and associates, which is based on a Cahn-Hilliard-type partial differential equation. This model regulates the progression of an order parameter $u \in [0,1]$, which approximates the original image specified over a confined, two-dimensional domain Ω [8]. Carrillo, Kalliadasis, Liang, and Perez assessed the usefulness of utilizing a modified Cahn-Hilliard inpainting filter for inputting damaged images into a classification neural network. Utilizing the Modified National Institute of Standards Technology (MNIST) dataset, their findings indicate

that this methodology markedly enhances prediction accuracy by as much as 50% in certain instances, particularly for low to moderate damage levels [9]. Dandan Jiang, Mejdi Azaiez, Alain Miranville, and Chuahju Xu suggested an upgraded Cahn-Hilliard-type inpainting model using a nonlocal diffusion operator. This model exhibits exceptional efficacy in rebuilding absent areas in photographs [10]. Anis Mohamed, Hamdi Houichet, and Anis Theljani used the Cahn-Hilliard equation to devise an efficient method for inpainting binary images, concentrating on the restoration of low-order structures, including edges and corners, and the augmentation of image borders. The numerical results demonstrate the model's accuracy in attaining objectives [11]. Martin, Lin, and Carola introduced a novel paradigm in image processing, namely binary image refinement utilizing the Cahn-Hilliard equation. They examined the equilibrium state of the model and introduced a generalization for grayscale images with constrained contrast. They achieved a structural refinement of images distinguished by a smooth curving of the gradient levels [12]. Qiumei, Jiaxuan, and Zhen introduced a mass-preserving adaptive time-scaling model for Physics-Informed Neural Network (PINN) that dynamically segments the time domain based on the energy decay rate. This model addressed the Cahn-Hilliard equations with an autonomous neural network, and the outcomes illustrated the efficacy of this technique [13].

Jessica and Martin devised a model employing the vector-valued Cahn-Hilliard equation. Numerical examples illustrate that the sanctioned fractional Cahn-Hilliard method of interior mapping surpasses its non-fractional counterpart, enhancing the signal-to-noise ratio and structure similarity index. Experiments validate that the suggested model is comparable to prior interior mapping techniques, including total variance and fourth-order variable interior mapping methods [14]. Antun, Darko, and Anderj proposed a novel nonlocal partial differential equation derived from the Cahn-Hilliard model for the purpose of image restoration. The suggested linear model exhibits lower computational costs compared to the Cahn-Hilliard equation while still delivering high-quality interior painting outcomes. An example of internal coloring was presented to demonstrate the method's possibilities [15]. Qing Zou introduced a fourth-order partial differential equation model for picture coloration, integrating the Perona-Malik and Cahn-Hilliard equations through the principle of energy partitioning.

The numerical results indicate that the suggested model demonstrates superior colorization performance with reduced calculation time relative to traditional PDE models [16]. Despite the extensive application of the Cahn-Hilliard equation in binary image inpainting, comprehensive research examining its performance over many color spaces and comparing its efficacy among various color models remains insufficient. The classical Cahn-Hilliard model is adopted due to its well-established physical and mathematical foundation, which enables rigorous analytical treatment and clear energy estimates. This choice allows us to isolate the effect of the color space representation without introducing additional nonlocal complexities. Although nonlocal Cahn-Hilliard extensions exist and are physically relevant, they are beyond the scope of the present work.This paper examines the application of the Cahn-Hilliard model across multiple color spaces (CMY, YCbCr, RGB, YUV, XYZ, NTSC, HSL, and HSV) as seen in [17], evaluates the visual analysis of the resultant images, and assesses their quality through statistical metrics including mean square error (MSE), peak signal-to-noise ratio (PSNR), structural similarity (SSIM) and entropy [18]. The rest of the paper is organized as follows: Section 2 elucidates the digital images. Section 3 introduces the concept of picture inpainting. Section 4 reviews color spaces and their suitability for Cahn-Hilliard image modeling. Section 5 presents the Cahn-Hilliard model. Section 6 presents and discusses several numerical results of the proposed model. Section 7 will present the conclusion.

2 DIGITAL IMAGE

A two-dimensional digital image is made up of a certain set of digital values, which are pixels. In an image, each pixel has a unique location x_{ij} and is linked to an intensity number d(x_{ij}) which tells you about the color, and as a number, each value in the image ranges from 0 to 255, with 0 being the least intense and 255 being the most intense. Each pixel in a greyscale image has a single intensity number that ranges from 0 (black) to 255 (white). When talking about color images, the RGB (red, green, and blue) color range is usually used. According to the specified model, each pixel in a color image has three numerical values, one from 0 to 255, which represent the strengths of the red, green, and blue parts [19].

3 IMAGE INPAINTING

Image inpainting is the process of using information from the surrounding field to recreate missing or damaged areas of an image so that the viewer is unaware of the changes [20]. The size and nature of the missing areas have a significant impact on this method's effectiveness. The visual result is better when the inpainting zone is smaller and the surrounding texture is simpler. The inpainting technique relies heavily on texture, which represents the regularity, smoothness, and coarseness of image parts. When damage arises from intentional scratching, ageing, or weathering, images can be effectively restored [21]. However, reconstruction becomes more difficult when a significant portion of the image is missing because the remaining portions do not provide essential contextual information.

4 COLOR SPACES

Color spaces are mathematical constructs that represent colors as numerical values, each tailored for certain uses such as image reduction, broadcasting, and picture restoration. They are typically classified into two categories: those that utilize primary channels directly, such as RGB and CMY, and those that differentiate luminance and chrominance, including YCbCr, YUV, HSV, HIS, and XYZ. In RGB, each channel has completed structural and chromatic information, potentially leading to discrepancies when channels are handled separately. In contrast, YCbCr and YUV separate luminance (Y) from chrominance (Cb, Cr), hence augmenting compression efficiency and strengthening edge preservation [22]. HSV and HSL offer a perceptually intuitive depiction of hue, saturation, and value, closely correlating with human color perception; nonetheless, they exhibit instabilities in the hue axis when saturation is absent [23]. The XYZ model provides a linear depiction of the spectrum and underpins perceptual models such as (CIE-Commission International de I'E`clairage) CIELAB, although it lacks perceptual uniformity. CIELAB is not perceptually uniform [24].

The suitability of the Cahn-Hillird model depends on how different color space representations capture image structures and perceptual consistency. In the Y channel of YCbCr, the model enhances edge integrity and diminishes noise; however, in RGB, it may result in inconsistencies among R, G, and B due to the independent processing of channels. The efficacy of inpainting is significantly influenced by the selection of color space: RGB is optimal for display, YCbCr/YUV for compression and restoration, HSV/HSL for perceptual design, and XYZ for scientific applications necessitating spectral accuracy [9].

5 MODIFIED CAHN-HILLIARD MODEL

One semi-linear fourth-order partial differential equation (PDE) developed for binary image inpainting is the modified Cahn-Hilliard (mCH) equation [3]. The field of material sciences uses this equation [24]. with $\vec{x} = (x, y)$ and let D⊂Ω represent the inpainting domain; let f($\vec{x}$) be a specified image defined throughout the domain Ω. The resolution of (1) under Neumann boundary conditions is employed to restore the compromised images. The implicit finite difference method is utilized to solve (1), while the convex partition of (6) and (7) is employed to provide numerical stability. The equation is given by:

$$\partial_t u = \Delta\left(-\epsilon\,\Delta u - \frac{1}{\epsilon}F(u)\right) + \lambda(\vec{x})(f(\vec{x}) - u), \quad \text{in } \Omega \quad (1)$$

$$\text{Where } (\vec{x}) = \begin{cases} 0 & if\ \vec{x} \in D \\ \lambda_0 & if\ \vec{x} \in \Omega \backslash D \end{cases}$$

Equation (1) is known as the mCH equation, and it includes an additional fidelity term $\lambda(\vec{x})\,(f(\vec{x}) - u)$. The function $F(u)$ is referred to as a double-well potential, given by $F(u) = 1/u(1-u)^2$, and ϵ is a tiny positive parameter that approaches zero. To solve (1), it is sufficient to minimize the following energy functions:

$$\int_\Omega \left(\frac{\epsilon}{2}|\nabla u|^2 + \frac{1}{\epsilon}f(u)\right) d\vec{x} + \lambda_0 \int_{\Omega\backslash D}(f-u)^2 d\vec{x}. \quad (2)$$

The initial component denotes the energy of a gradient flow based on the H^{-1}-norm, resulting in the mCH equation, whereas the subsequent component is a fidelity term derived from a gradient flow utilizing the L^2-norm. This process is similar to the convexity splitting used in an isotropic framework. Diffusion inpainting functions under a fourth-order total variation framework. The fitting term represents a gradient flow in $H^{-1}(\Omega)$. The fitting term represents a gradient flow in $H^{-1}(\Omega)$. The fidelity term is considered on $L^2(\Omega)$. In this context, $H^{-1}(\Omega)$ is the dual Sobolev space of $H_0^1(\Omega)$, with the associated norm defined as:

$$\|f\|_{-1}^2 = \|\nabla\Delta^{-1}f\|_{-1}^2 = \int_\Omega (\nabla\Delta^{-1})^2 d\vec{x} \quad (3)$$

Where Δ^{-1}refers to the inverse of the Laplace operator, such that $u = \Delta^{-1}f$ is $-\Delta u = f$ in Ω, with $u = 0$ on $\partial\Omega$. Let:

$$R_1 = \int_\Omega \left(\frac{\epsilon}{2}|\nabla u|^2 + \frac{1}{\epsilon}F(u)\right) d\vec{x}, \quad (4)$$

$$R_2 = \lambda_0 \int_{\Omega\setminus D} (f-u)^2 d\vec{x} \quad (5)$$

Convexity splitting is applied separately to R_1 and R_2 decomposed as:

Where $R_1 = R_{11} - R_{12}$, then

$$R_{11} = \int_\Omega \left(\frac{\epsilon}{2}|\nabla u|^2 + \frac{C_1}{2}|u|^2\right) d\vec{x}, \quad (6)$$

$$R_{12} = \int_\Omega \left(-\frac{1}{\epsilon} + F(u) + \frac{C_1}{2}|u|^2\right) d\vec{x} \quad (7)$$

Likewise $R_2 = R_{21} - R_{22}$, where:

$$R_{21} = \int_{\Omega\setminus D} \frac{C_2}{2}|u|^2 d\vec{x}, \quad (8)$$

$$R_{22} = \int_{\Omega\setminus D} (-\lambda_0(f-u)^2) + \frac{C_2}{2}|u|^2 d\vec{x} \quad (9)$$

Based on the above, the resulting time-stepping scheme is given by:

$$\frac{u^{n+1}-u^n}{k} + \epsilon\nabla^4 u^{n+1} - C_1\nabla^2 u^{n+1} + C_2 u^{n+1} = \nabla^2\left(\frac{1}{\epsilon}f'(u^n) + \lambda(\vec{x})(f(\vec{x}) - u^n)\right) - C_1\nabla^2 u^n + C_2 u^n \quad (10)$$

We enforce Neumann boundary conditions on $\partial\Omega$. $\nabla U_{k+1}.\vec{n} = \nabla\Delta U_{k+1}.\vec{n} = 0$, $\left(\frac{\partial u}{\partial n} = 0,\ \frac{\partial(\Delta u)}{\partial u} = 0\right)$, on $\partial\Omega$.

The significance of this model lies in its ability to restore large missing regions without introducing artefacts [3]. The overall workflow of the proposed Cahn-Hilliard inpainting process is summarized in Figure 1, which illustrates the sequential steps from initialization, application of the modified PDE, convexity splitting, to the final image reconstruction.

6 NUMERICAL EXPERIMENTS AND RESULTS

The proposed Cahn-Hilliard model was implemented on 80 color images from the Berkeley Color Database [25], which includes high-texture color images. As shown in Figure 2, two experiments were conducted using the model and color spaces described earlier.

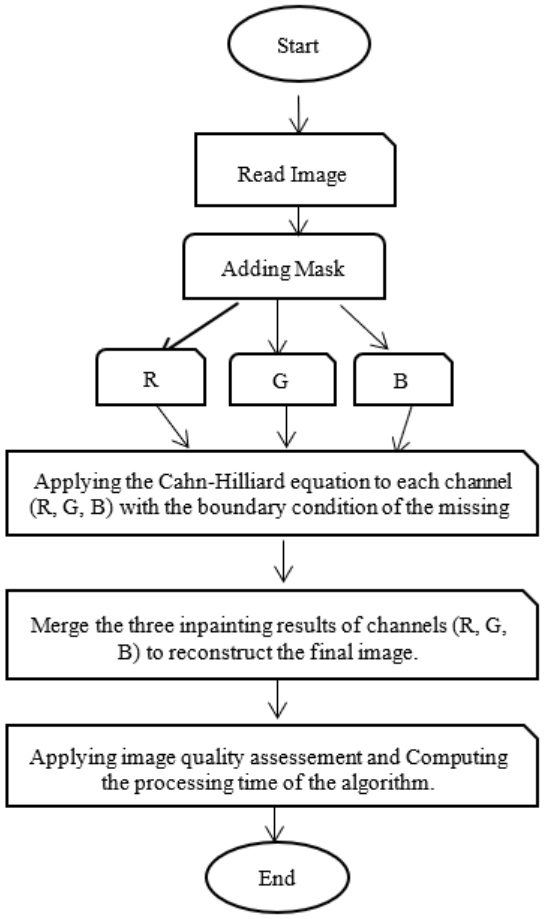


Figure 1: Flowchart of inpainting process using Cahn-Hilliard.



Figure 2: Example of four out of 300 trained natural images.

The process of image inpainting may be explained in the following way: $D \subset \Omega$ stands for the inpainting domain, $f: \Omega \longrightarrow R^{+1}$ for the specified image, and Ω for the image domain. Binary masks were used to create four instances of intrinsic

inpainting domains, which are damaged regions, in the image. Here is an equation that shows scratches and text may be added to the original image: f is the original image, M is the mask image, and M^{-1} is the logical inverse of the mask image.

$$f_{Damaged} = M^{-1}(x,y) \times f(x,y) + M\,(x,y). \quad (11)$$

As illustrated in Figure 3, the masks were selected based on the breadth of M, the scratches; specifically, the first two masks illustrate scratches of varying widths, which indicate minor damaged areas. The third mask depicts a big scratch, indicating vast damaged areas. Lastly, the fourth mask includes two missing blocks. The four masks will be applied to a series of high-texture, natural-colored photographs, as previously stated. To replace each image's missing parts, we will put the Cahn-Hilliard model into practice. After that, we use Structural quality measures (SQMs), including structural similarity indices (SSIM) [26], peak signal-to-noise ratio (PSNR) [27], mean square error (MSE) [28], and the information entropy of both the input image (E_0) and the output image E_1. To visually and statistically compare the experiment outcomes.

These SQMs are used to evaluate the model's efficiency in terms of its ability to retrieve missing regions from the image. The time taken to obtain results was also studied, and the image recovery was implemented in MATLAB code (elapsed for MATLAB R2020a, running on a laptop with an Intel (R) Core (TM) i7-9850H CPU at 2.60 GHz and 32 GB of RAM). Two experiments were conducted in this section. Section 6.1 presents an experiment analyzing the model's behavior on missing regions of different sizes; Section 6.2 presents an experiment analyzing the model's behavior on different numbers of iterations.

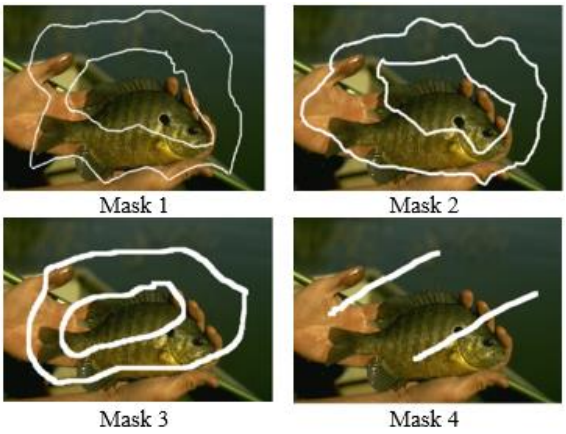


Figure 3: Illustrates the types of image masks, each with different missing areas.

6.1 Different Types of Missing Areas

In this section, four experiments were conducted, and their results were presented in four tables. Four different masks were adopted, representing different levels of damage in the images, with each mask varying in the area of the deleted region. To achieve the accuracy and stability of the results, processing was performed using a different iteration for each mask. These experiments were applied to images after converting them to eight different color spaces. The goal was to evaluate the model's performance across multiple color contexts and determine the color space that offers the best performance. The color space performance was correlated with the damage level (mask) to determine whether the mask type directly affects the effectiveness of the color space. And as shown in the Tables 1 - 4.

Table 1: The average values of MSE, PSNR, SSIM, and entropy for image inpainting using the Cahn-Hilliard equation in MASK 1 at iteration 50.

SPACES	MSE	PSNR	SSIM	E_0	E_1	Time(s)
YCbCr	129.4358	28.52194	0.996911	7.150389	7.132853	3.2793
YUV	129.4525	28.5211	0.996911	7.150389	7.132865	3.7909
NTSC	129.4564	28.5203	0.996916	7.150389	7.132804	3.401
CMY	129.5468	28.51616	0.996911	7.150389	7.132109	3.2976
RGB	129.5593	28.51598	0.996913	7.150389	7.132185	4.3965
HSL	133.7117	28.33284	0.996784	7.150389	7.132971	3.4191
XYZ	140.2804	28.13715	0.996444	7.150389	7.145394	3.6312
HSV	146.3791	27.59021	0.996544	7.150389	7.140073	3.3785

Table 2: The average scores of MSE, PSNR, SSIM, and entropy for filling in the image using the Cahn-Hilliard equation in MASK 2 after 100 iterations.

SPACES	MSE	PSNR	SSIM	E_0	E_1	Time(s)
RGB	238.6114	25.70954	0.994181	7.150389	7.132164	5.8563
CMY	238.6429	25.70864	0.994174	7.150389	7.132075	5.8694
NTSC	238.6943	25.70794	0.99418	7.150389	7.132924	5.9029
YUV	238.9249	25.70575	0.994165	7.150389	7.133233	6.282
YCbCr	238.9501	25.70566	0.994164	7.150389	7.13319	5.9514
HSL	245.7121	25.55883	0.993996	7.150389	7.133219	5.8508
XYZ	251.0125	25.45771	0.993522	7.150389	7.145744	5.9259
HSV	262.6121	25.1639	0.993749	7.150389	7.139844	5.751

Table 3: The mean values of MSE, PSNR, SSIM, and entropy for image inpainting using the Cahn-Hilliard equation in MASK 3 at iteration 250.

SPACES	MSE	PSNR	SSIM	E_0	E_1	Time(s)
CMY	444.3194	22.74889	0.977894	7.150389	7.13198	14.0398
RGB	445.7759	22.7349	0.977957	7.150389	7.134693	14.0332
NTSC	446.0363	22.73104	0.977948	7.150389	7.137225	13.342
YCbCr	448.1505	22.70714	0.977899	7.150389	7.139373	13.8648
YUV	448.2783	22.70618	0.977893	7.150389	7.139736	14.2992
HSL	468.6999	22.46513	0.977565	7.150389	7.136658	16.7154
HSV	481.466	22.35831	0.977296	7.150389	7.14076	13.48
XYZ	490.6576	22.22118	0.975891	7.150389	7.151723	13.9947

Table 4: The average scores for MSE, PSNR, SSIM, and entropy for image inpainting using the Cahn-Hilliard equation in MASK 4 at iteration 300.

SPACES	MSE	PSNR	SSIM	E_0	E_1	Time(s)
CMY	442.0186	23.05999	0.991994	7.150389	7.132155	19.1881
RGB	443.626	23.03534	0.992016	7.150389	7.133326	16.5651
NTSC	444.3275	23.0302	0.992009	7.150389	7.134341	16.5168
YUV	446.0074	23.00626	0.992	7.150389	7.135559	17.0714
YCbCr	446.0081	23.0061	0.991999	7.150389	7.13534	16.5636
HSL	468.3886	22.76904	0.991785	7.150389	7.134586	18.7603
XYZ	477.9063	22.64644	0.991507	7.150389	7.14782	16.4762
HSV	483.4296	22.6306	0.991736	7.150389	7.141024	16.3957

The first experiment involved 50 iterations of the numerical operation on a small erased region (Table 1). The color spaces are arranged from best to worst according to the MSE values. YCbCr achieved the best reconstruction accuracy, exhibiting the lowest MSE. In terms of other image quality metrics (PSNR and SSIM), NTSC, YCbCr, and YUV outperformed HSV, HSL, and XYZ. However, the maximum entropy (7.145394) was observed in XYZ, indicating higher information diversity or noise. Regarding computational time, RGB and YUV were the slowest, whereas CMY and YCbCr were the fastest.

The results after 100 iterations are summarized in Table 2. Again, the color spaces are ranked according to MSE. The best MSE, PSNR, and SSIM were obtained in RGB, while HSV was the fastest despite having the worst MSE and PSNR. XYZ exhibited the highest entropy (7.145744).

In Table 3, 250 iterations were performed on a large missing region (mask 3). CMY achieved the best MSE and PSNR, whereas RGB had the highest SSIM. The weakest performance was observed for XYZ. NTSC was the fastest, and HSL the slowest. Among all spaces, XYZ showed the smallest difference between Entr1 and Entr0.

Table 4 presents results for 300 iterations. CMY again had the best MSE and PSNR, while HSV performed the worst. RGB achieved the highest SSIM, and XYZ had the lowest entropy.

Based on these experiments, RGB demonstrated the best overall performance in terms of numerical accuracy (MSE), perceptual quality (PSNR, SSIM), and structural similarity. Figure 4 illustrates examples of restored images for four masks in the RGB space.

6.2 Different Iterations of Numerical Solutions

In this section, we conducted eight experiments across a variety of color spaces. We studied the behavior of the model for four different mask sizes, each with its unique size. For each mask, we performed four different iterations, each varying from one mask to another. The experimental results were evaluated using a set of statistical metrics. The goal of the experiment was to determine the relationship between the number of iterations, the mask type and the performance of color spaces to achieve the best restoration quality while, calculating execution time to ensure acceptable time efficiency. The adopted iterations for the masks were in the first mask (1, 10, 20, 50); in the second mask (1, 25, 50, 100); in the third mask (50, 100, 150, 250); and finally in the fourth mask (100, 150, 200, 300). Tables 5-8 show the experimental results for eight spaces. Figure 5 below illustrates the visual study of the outcomes in the RGB space for the restoration of ideal mask 1 across four iterations.

Table 5: The mean values of MSE, PSNR, SSIM, and entropy for image inpainting performed with the Cahn-Hilliard equation in eight spaces in MASK 1 at different iterations.

SPACES	Iteration	MSE	PSNR	SSIM	E_o	E_I	Time(s)
YCbCr	1	3165.246	13.50443	0.95616	7.150389	7.059599	1.0179
	10	341.7871	23.07316	0.988663	7.150389	7.170919	1.4241
	20	143.4894	27.72096	0.996074	7.150389	7.13996	1.8428
	50	129.4358	28.52194	0.996911	7.150389	7.132853	3.3896
YUV	1	3720.908	12.75597	0.952901	7.150389	7.063469	1.26605
	10	341.5751	23.07634	0.988666	7.150389	7.72933	1.7073
	20	143.5141	27.72095	0.996073	7.150389	7.140531	2.2896
	50	129.4525	28.5211	0.996911	7.150389	7.132865	3.7909
NTSC	1	1264.155	17.58749	0.973349	7.150389	7.031703	0.9002
	10	311.6674	23.54745	0.989584	7.150389	7.166328	1.3387
	20	141.748	27.81553	0.996169	7.150389	7.138831	1.8634
	50	129.4564	28.5203	0.996916	7.150389	7.132804	3.3378
CMY	1	3016.431	13.78254	0.938621	7.150389	6.923821	0.9024
	10	258.1104	24.57675	0.994465	7.150389	7.131321	1.3112
	20	138.8738	27.97146	0.99669	7.150389	7.132268	1.8128
	50	129.5468	28.51616	0.996911	7.150389	7.132109	3.2976
RGB	1	4877.128	11.43425	0.947441	7.150389	6.999926	0.8949
	10	304.252	23.64348	0.989634	7.150389	7.145318	1.3348
	20	141.6216	27.82485	0.996171	7.150389	7.135334	1.8143
	50	129.5593	28.51598	0.996913	7.150389	7.132185	4.3965
HSL	1	3298.814	13.13769	0.956141	7.150389	7.068999	0.9204
	10	449.4215	21.99576	0.986982	7.150389	7.155859	1.3773
	20	163.4075	26.98501	0.995595	7.150389	7.13779	1.8711
	50	133.7117	28.33284	0.996784	7.150389	7.132971	3.3483
XYZ	1	6823.633	10.02331	0.939318	7.150389	6.923334	1.0118
	10	784.4291	19.57025	0.97937	7.150389	7.174031	1.4384
	20	215.9553	25.59298	0.992207	7.150389	7.153446	1.9461
	50	140.2804	28.13715	0.996444	7.150389	7.145394	3.4367
HSV	1	1293.183	17.66026	0.974549	7.150389	6.995213	0.9032
	10	282.0068	24.07335	0.99104	7.150389	7.150298	1.3504
	20	146.3791	27.59021	0.996149	7.150389	7.142936	1.8748
	50	153.6056	27.7542	0.996544	7.150389	7.140073	3.3501

Table 6: The mean results of MSE, PSNR, SSIM, and entropy for image inpainting using the Cahn-Hilliard equation in eight spaces in MASK 2 at different iterations.

SPACES	Iteration	MSE	PSNR	SSIM	E_o	E_I	Time(s)
YCbCr	1	4402.113	12.07889	0.950719	7.150389	7.075903	1.7199
	25	400.845	22.51144	0.989096	7.150389	7.17589	2.1576
	50	245.0842	25.42381	0.993853	7.150389	7.139683	3.4039
	100	238.9501	25.70566	0.994164	7.150389	7.13319	5.9423
YUV	1	5230.198	11.28716	0.947083	7.150389	7.079419	2.4123
	25	400.6006	22.51483	0.989099	7.150389	7.177643	2.4492
	50	245.1169	25.42369	0.993852	7.150389	7.140273	3.6873
	100	238.9249	25.70575	0.994165	7.150389	7.133233	6.282
NTSC	1	1771.119	16.14835	0.968592	7.150389	7.075834	1.9118
	25	373.097	22.89856	0.989762	7.150389	7.167958	2.0869
	50	243.784	25.4708	0.9939	7.150389	7.137823	3.3001
	100	238.6943	25.70794	0.99418	7.150389	7.132924	5.9473
CMY	1	4695.988	11.85383	0.922636	7.150389	6.958289	1.671
	25	333.3885	23.57936	0.99286	7.150389	7.131619	2.0665
	50	243.3636	25.50248	0.99407	7.150389	7.131169	3.2999
	100	238.6429	25.70864	0.994174	7.150389	7.132075	5.8694
RGB	1	7494.983	9.57385	0.939702	7.150389	7.051214	1.219
	25	367.0325	22.97309	0.989799	7.150389	7.148879	2.0514
	50	243.6413	25.47474	0.993904	7.150389	7.134506	3.296
	100	238.6114	25.70954	0.994181	7.150389	7.132164	5.8563
HSL	1	5570.518	10.869	0.947689	7.150389	7.121845	1.8412
	25	516.3749	21.47701	0.98774	7.150389	7.158126	2.0881
	50	264.7761	24.96655	0.993505	7.150389	7.137085	3.3145
	100	245.7121	25.55883	0.993996	7.150389	7.133219	5.8641
XYZ	1	10034.86	8.347463	0.931651	7.150389	6.947726	2.3892
	25	816.8024	19.42884	0.981041	7.150389	7.18315	2.1833
	50	303.7746	24.22331	0.991181	7.150389	7.152949	3.4675
	100	251.0125	25.45771	0.993522	7.150389	7.145744	6.0226
HSV	1	1791.552	16.21623	0.969203	7.150389	7.05778	1.8365
	25	357.1924	23.13484	0.990605	7.150389	7.153898	2.1132
	50	253.8277	25.16754	0.993703	7.150389	7.14225	3.2635
	100	262.6121	25.1639	0.993749	7.150389	7.139844	5.8176



Figure 4: Examples of inpainting images. (a) Original images, (b) Mask images, (c) Inpainted images according to Cahn-Hilliard equation.

Table 7: The average measurements of MSE, PSNR, SSIM, and entropy for image inpainting using the Cahn-Hilliard equation in eight spaces in MASK 3 at different iterations.

SPACES	Iteration	MSE	PSNR	SSIM	E_o	E_I	Time(s)
YCbCr	50	1756.245	15.8466	0.959638	7.150389	7.271531	3.3461
	100	713.376	19.95439	0.971293	7.150389	7.202233	5.7492
	150	498.6449	21.91925	0.976028	7.150389	7.164529	8.6225
	250	448.1505	22.70714	0.977899	7.150389	7.139373	14.1383
YUV	50	1743.566	15.87916	0.959812	7.150389	7.268519	3.6137
	100	713.2994	19.95624	0.971299	7.150389	7.204938	6.1898
	150	498.6918	21.91908	0.976027	7.150389	7.166223	8.7557
	250	448.2783	22.70618	0.977893	7.150389	7.139736	14.2992
NTSC	50	1365.8	17.03396	0.961761	7.150389	7.234925	3.3647
	100	655.9176	20.37605	0.972177	7.150389	7.187393	5.7966
	150	483.805	22.10149	0.976392	7.150389	7.155629	8.4965
	250	446.0363	22.73104	0.977948	7.150389	7.137225	13.7396
CMY	50	1083.13	18.15948	0.96918	7.150389	7.133953	3.3231
	100	562.7513	21.25241	0.975637	7.150389	7.130045	5.8847
	150	462.9449	22.39461	0.977323	7.150389	7.130005	8.3085
	250	444.3194	22.74889	0.977894	7.150389	7.13198	14.0398
RGB	50	1482.098	16.59438	0.961832	7.150389	7.201906	3.2928
	100	648.3756	20.43904	0.972334	7.150389	7.1608	5.8797
	150	482.8686	22.11798	0.976422	7.150389	7.14397	8.2933
	250	445.7759	22.7349	0.977957	7.150389	7.134693	14.0332
HSL	50	1780.958	15.87768	0.959759	7.150389	7.224463	3.3677
	100	859.031	19.19395	0.970393	7.150389	7.170281	5.8478
	150	590.2388	21.08679	0.97516	7.150389	7.150425	8.4316
	250	468.6999	22.46513	0.977565	7.150389	7.136658	13.8891
XYZ	50	3089.263	13.52654	0.950154	7.150389	7.261341	3.4565
	100	1285.04	17.40549	0.963558	7.150389	7.201464	5.9382
	150	720.7941	20.09725	0.97071	7.150389	7.172338	8.2894
	250	490.6576	22.22118	0.975891	7.150389	7.151723	13.9795
HSV	50	911.0818	18.78756	0.967193	7.150389	7.189668	3.4545
	100	600.904	20.84083	0.973643	7.150389	7.159231	5.7921
	150	507.4896	21.82613	0.976241	7.150389	7.148503	8.4356
	250	481.466	22.35831	0.977296	7.150389	7.14076	13.6727

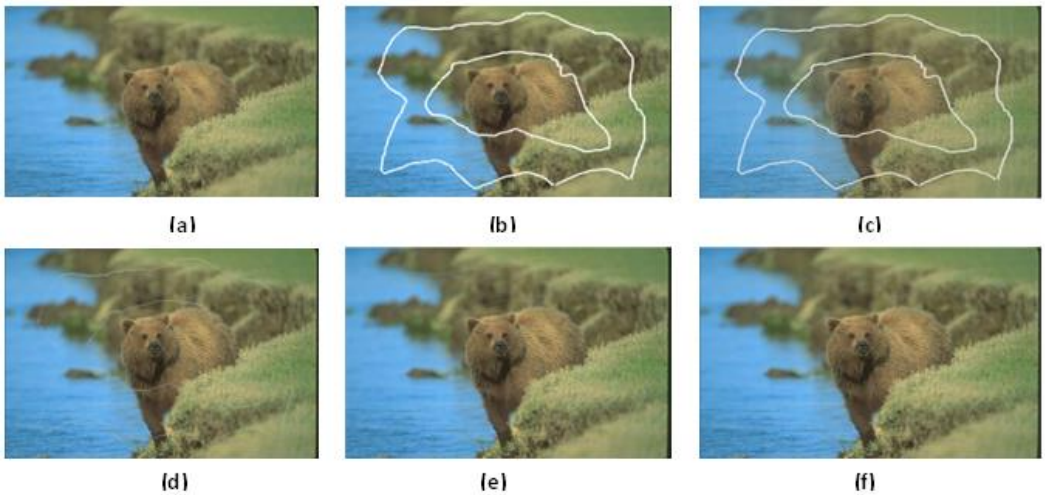


Figure 5: Examples of inpainting images: a) Original image, b) Mask image, c), d), e), and f) Inpainted images by Cahn-Hilliard when iterations are (1, 10, 20, and 50, respectively).

Table 8: The mean values of MSE, PSNR, SSIM, and entropy for image inpainting performed with the Cahn-Hilliard equation in eight spaces in MASK 4 at different iterations.

SPACES	Iteration	MSE	PSNR	SSIM	E_o	E_I	Time(s)
YCbCr	100	840.4149	19.24566	0.989036	7.150389	7.168335	6.0104
	150	542.0065	21.56051	0.990956	7.150389	7.15096	8.6905
	200	466.2394	22.58638	0.991713	7.150389	7.142035	11.1672
	300	446.0081	23.0061	0.991999	7.150389	7.13534	16.2808
YUV	100	840.4708	19.24901	0.989041	7.150389	7.16992	6.2791
	150	541.9464	21.56226	0.990959	7.150389	7.152089	8.6339
	200	466.2181	22.5857	0.991715	7.150389	7.142635	11.3377
	300	446.0074	23.00626	0.992	7.150389	7.135559	17.0714
NTSC	100	751.4746	19.79615	0.989409	7.150389	7.160778	5.9398
	150	515.7375	21.85865	0.991148	7.150389	7.146134	8.4854
	200	458.0235	22.71281	0.991782	7.150389	7.139135	11.2168
	300	444.3275	23.0302	0.992009	7.150389	7.134341	16.067
CMY	100	641.2911	20.78006	0.990752	7.150389	7.130641	5.6369
	150	483.525	22.33204	0.991614	7.150389	7.130373	8.4411
	200	447.3168	22.8912	0.991881	7.150389	7.130893	13.5895
	300	442.0186	23.05999	0.991994	7.150389	7.132155	19.1881
RGB	100	743.4341	19.85199	0.989515	7.150389	7.147591	5.787
	150	514.2454	21.8833	0.991171	7.150389	7.139859	8.4372
	200	457.7541	22.71671	0.991787	7.150389	7.135914	11.1094
	300	443.626	23.03534	0.992016	7.150389	7.133326	16.5651
HSL	100	991.0061	18.65478	0.988854	7.150389	7.151863	5.9125
	150	684.4718	20.51923	0.99049	7.150389	7.143669	8.5589
	200	533.1117	21.88933	0.991372	7.150389	7.138311	11.1309
	300	468.3886	22.76904	0.991785	7.150389	7.134586	16.4884
XYZ	100	1519.686	16.75016	0.986419	7.150389	7.173889	5.994
	150	838.7148	19.49555	0.989	7.150389	7.161115	8.5032
	200	592.1172	21.30653	0.990479	7.150389	7.153944	10.9898
	300	477.9063	22.64644	0.991507	7.150389	7.14782	16.5856
HSV	100	637.8425	20.6598	0.99027	7.150389	7.149519	5.8829
	150	537.2672	21.67579	0.991179	7.150389	7.145386	8.3959
	200	489.3065	22.35145	0.99159	7.150389	7.142779	11.0514
	300	483.4296	22.6306	0.991736	7.150389	7.141024	16.06

The above tables showed the final results as follows:

1) The first and second masks (Tables 1, 2) achieved the best performance when using the YCbCr space at 50 iterations and the RGB space at 100 iterations, where image reconstruction was high-resolution and relatively short [10]. This is due to the structural properties of the YCbCr and RGB spaces. The YCbCr space separates the image components into the luminance (Y) component and the color (Cb, Cr) components [29]. This separation is very useful for recovering small missing regions because it allows for more accurate and efficient processing [10]. The proposed Cahn-Hilliard model enables focusing on the important visual details in the Y channel while allowing some tolerance in the Cb and Cr color channels without affecting the quality of the recovered image. Therefore, this space is used in techniques (compression, restoration, etc.) [9]. Therefore, the RGB space requires a larger number of iterations (100) to improve accuracy [10].
2) In the third and fourth masks (Tables 3, 4), the CMY and RGB spaces achieved the best values in terms of MSE, PSNR, and SSIM. This is because the RGB and CMY color spaces represent colors directly, which allows for accurate reconstruction of large deleted areas. But they recorded the highest difference in entropy, indicating a significant amount of information change between the original and processed images, since the two spaces do not separate the lighting and color components. And because processing images in RGB and CMY spaces requires more calculations, it leads to increased execution time [30], [31].

3) The HSV space was approximately the fastest to execute, but it recorded poor results on the (MSE, PSNR, and SSIM) metrics. This is because the HSV space is primarily designed for color correction applications and not for pixel retrieval. Although it separates hue from value, this separation is not suitable for retrieving the original image structure. This renders it unfit for retrieving and enhancing high-resolution images, where image quality takes precedence over time [32]. The XYZ space had the lowest entropy difference of all the spaces, indicating that the image retained its information values after processing. The result may indicate that the changes did not significantly affect the image, and therefore, the XYZ space did not significantly improve it. This is because XYZ space is a theoretical color space designed to accurately represent colors according to the human visual model, without taking into account process ability or visual
enhancement [33].
4) We obtained lower MSE values and higher SSIM and PSNR; the execution time was faster in the first and second masks (Tables 5, 6). The Cahn-Hilliard equation can accurately retrieve the image because the surrounding pixels provide sufficient spatial and color information [9]. In contrast, the third and fourth masks had a large missing region (Tables 7, 8), so we required more time. We observed a significant increase in MSE values and a significant decrease in PSNR and SSIM values. The result indicates that the processed image differs significantly from the original image in terms of pixel values, structure, and visual content. This variation is because the retrieval algorithm lacks sufficient indifrom the original image, making it difficult to reconstruct structures and details, even with an increasing number of iterations (250, 300) [8].

7 CONCLUSIONS

The Cahn-Hilliard phase diffusion model was employed to reconstruct absent areas in images and was utilized across diverse images and configurations of missing regions. The proposed approach was executed in tests that encompassed many iterations and eight distinct color spaces. The findings indicated a strong correlation between the magnitude of the absent region and the number of iterations employed, since both influence the quality of retrieval. It was noted that small masks necessitated fewer iterations to attain satisfactory results, but masks with extensive missing areas demanded more iterations to acquire acceptable outcomes. The findings underscore the necessity of balancing the extent of the missing area, the iteration count, and the choice of a suitable color space to optimize future image retrieval. Based on the overall analysis of the results, it can be concluded that the model demonstrated stable preformance and several positive characteristics that confirm its effectiveness in image processing across different color spaces. The findings revealed that the selection of the color space has a direct impact on enhancing the quality of the reconstructed image and reducing numerical error, as the variation among spaces clarified the model's behavior toward spatial structure and color information. The experiments also showed that th interaction between the model and the missing regions depends on balancing visual properties and numerical accuracy.

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Fuzzy Logic-Based Evaluation of IoT Training Simulators

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Abstract: Developers offer various options for virtual simulators that allow training in diagnosing Internet of Things (IoT) systems. To select devices with the best characteristics, as well as to identify shortcomings and improve virtual simulators, tools for assessing their characteristics are in demand. An adequate selection of virtual simulators with the best characteristics, as well as the identification of their shortcomings for subsequent improvement, are urgent research problems. The presented research is aimed at solving these problems. A system has been developed for assessing the characteristics of virtual simulators intended for IoT systems training in diagnosis. It is based on the use of fuzzy logical inference. As indicators for assessing the characteristics of virtual simulators used for training IoT systems in diagnosis, it is proposed to use indicators of image realism, sound realism and diversity of training scenarios sets, as well as a general indicator of virtual simulator functioning. The parameters of the membership functions of fuzzy sets and individual outputs of fuzzy rules were automatically selected using a neural network setup. In order to study the proposed fuzzy logical inference system, a model of the process of assessing the virtual simulators characteristics intended for IoT systems training in diagnosis has been developed in the MATLAB software environment using the libraries of the Simulink package. Numerous computational experiments have been carried out using this software model. A comparison of their results with the results of real IoT systems diagnosing showed that the higher the values of the generalized indicator of the virtual simulator functioning, the greater the probability of correct diagnosis of IoT systems by the specialists who trained on it. Thus, the proposed fuzzy inference system can be recommended for evaluating the characteristics of virtual simulators designed to teach diagnostics of Internet of Things systems.

1 INTRODUCTION

A promising scientific and technological direction is the creation of virtual simulators that help to learn the skills of diagnosing and monitoring the correct operation of various technical systems. The object of our research was virtual simulators used to acquire skills in diagnosing the operation of Internet of Things (IoT) systems. The scope of Internet of Things systems application includes applications for smart home [1], industry [2], healthcare [3], [4], ecology [5], energy [6], construction [7] and others [8].Currently, manufacturers offer various options for virtual simulators, specializing in smart city systems [9], smart agriculture [10], smart manufacturing [11] and other IoT applications [12]. Such software facilitates the process of Mastering the specifics of IoT devices setting up and operating, building wireless Internet of Things networks and detecting their incorrect operation. An urgent task is to develop tools for evaluating such virtual simulators. Such evaluation tools are necessary to select devices with the best.

Mastering the specifics of IoT devices setting up and operating, building wireless Internet of Things networks and detecting their incorrect operation. An urgent task is to develop tools for evaluating such virtual simulators. Such evaluation tools are necessary to select devices with the best characteristics, as well as to identify shortcomings to improve.

The relevant research problems are the adequate selection of virtual simulators with the best characteristics, as well as the identification of their shortcomings for subsequent improvement. Adequate

assessment tools for such virtual simulators are needed to solve these problems.

Many studies have been devoted to evaluating the effectiveness of virtual simulators. In particular, an assessment of the effects resulting from the use of VR games for teaching engineering sciences is presented [13]. Work [14] It is devoted to evaluating the usefulness of a hysteroscopic surgery simulator. The study of students' perception of a virtual simulator designed to acquire fire extinguishing skills is presented [15]. The assessment of the success of mastering the necessary skills using a dental simulator was performed [16]. A method for evaluating the performance of helicopter rescue crews trained using virtual reality scenarios is proposed [17]. The advantages of the above studies are that they provide an opportunity to show that the use of virtual simulators can improve the effectiveness of training. The disadvantages of the available means of evaluating the effectiveness of the use of virtual simulators in various fields include the fact that they are based mainly on the use of subjectively compiled questionnaires and do not have the necessary theoretical justification. In addition, an analysis of publications has shown that insufficient attention is paid to evaluating the characteristics of virtual simulators used for training in the diagnosis of Internet of Things networks.

The significance of this study is to improve the process of evaluating the characteristics of virtual simulators used for training in the diagnosis of Internet of Things networks. This improvement is proposed based on the development of a new evaluation system for virtual simulators, which is based on the use of mathematical fuzzy inference.

2 CREATION AND CONFIGURATION OF A FUZZY LOGICAL INFERENCE SYSTEM

In order to evaluate the characteristics of virtual simulators, it is proposed to create a system based on fuzzy logical inference. The scientific reasoning behind this proposal is that the mathematical apparatus of fuzzy logical inference is successfully used to solve many applied problems [18] - [22], including tasks related to estimating various quantities [23] - [26]. A neural network was used to adjust the parameters of the fuzzy inference system. For this purpose, neural network tools were used, which are created in the MATLAB-Simulink software environment and are used to solve many problems [27] - [30].

In the process of forming a training sample for neural network setup, it is necessary to make some surveys. Each test person should learn how to diagnose IoT systems using one virtual simulator. The person then has the opportunity to evaluate the performance of the virtual simulator according to three criteria: image realism (IR), sound realism (SR), and variety of training scenario sets (VAR). Scores for these criteria are given on a scale from 1 (lowest score) to 10 (highest score).

After training, the person tests the functioning of real IoT systems and diagnoses their malfunctions. The diagnosis accuracy is assessed by the value DR=0 if the person incorrectly diagnoses the technical condition of the IoT system, and by the value DR=1 in the case of an error-free diagnosis. The assessments of the virtual simulator characteristics and the values of the correct diagnosis of the technical condition of the IoT system received from the test person are entered into a special relational database, a fragment of which is presented in Table 1.

Table 1: Fragment of the training sample.

Training sample line number	IR	SR	VAR	DR
1	9	9	8	1
2	8	7	6	1
3	4	5	3	0
…	…	…	…	…
800	5	7	9	1

The training sample presented in Table 1 contains 800 rows. To form it, it is necessary to involve 200 persons, each of whom evaluates the virtual simulator characteristics, and then diagnoses the operation of 4 real IoT systems. The training data obtained in this way is used to configure the neural network for the fuzzy inference system.

The created fuzzy inference system uses three input variables that characterize the image realism, the sound realism and the variety of training scenarios provided by the virtual simulator. At the output, the system produces the VSI value of a generalized indicator of the virtual simulator functioning.

The creation and configuration of the fuzzy logical inference system was carried out in the MATLAB software environment using the anfisedit command. Two triangular membership functions were used to fuzzily each input variable. The zero-order Sugeno algorithm was chosen as a fuzzy inference algorithm, which has been successfully

used to create various fuzzy control systems [31] - [33].

The system was configured over 200 training cycles. For training, a hybrid algorithm was used that implements a combination of the least squares method and the inverse gradient descending method [34] - [36]. In Figure 1, you can observe how the training error gradually decreases and reaches values close to zero after the 110th cycle of the system configuration.

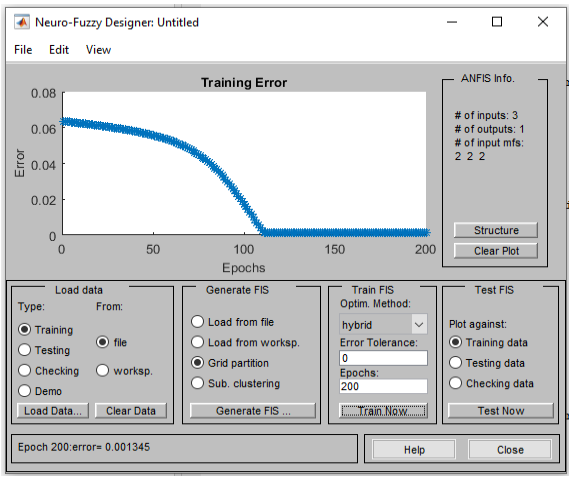


Figure 1: Setting up a fuzzy logical inference system.

The setup of the created fuzzy logical inference system is carried out using the generated neural network structure presented in Figure 2. This structure is a multilayer fuzzy neural network (Adaptive Neuro-Fuzzy Inference System, ANFIS), each layer of which serves to perform one or another fuzzy logical inference procedure in accordance with the zero-order Sugeno algorithm.

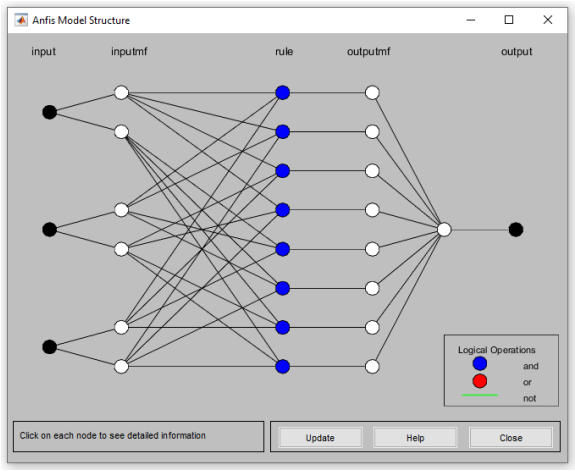


Figure 2: Structure of the ANFIS system.

Values of the membership functions parameters of input variables and individual outputs of fuzzy rules are automatically selected as a result of the execution of ANFIS training cycles. These values make the training errors minimal.

The fuzzy inference system configured in this way can be used to evaluate the characteristics of virtual simulators intended for t training in diagnostics of Internet of Things devices. As a result of system creating and configuration, 8 fuzzy rules were formed, the appearance of which is presented in Figure 3.

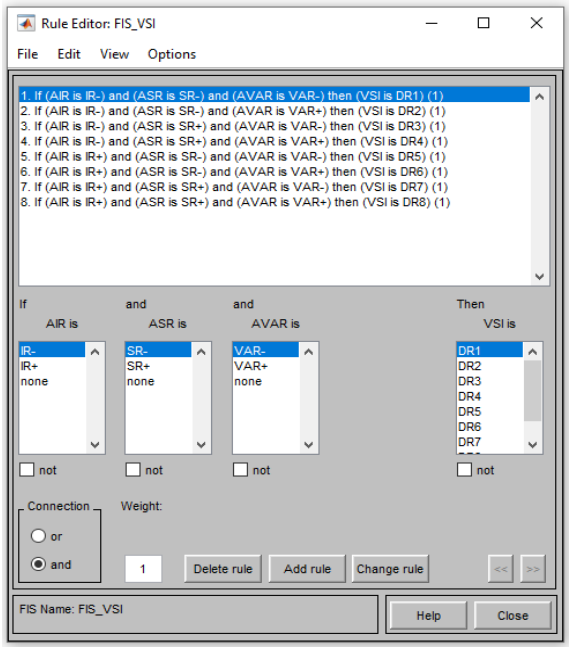


Figure 3: Basis of fuzzy rules.

The fuzzy rules include the following values: AIR is the average value for assessing the image realism; IR^+ is the fuzzy set “high value assessment of image realism”; IR^- is the fuzzy set “small value assessment of image realism”; ASR is the average value of sound realism assessment; SR^+ is the fuzzy set “high value of sound realism assessment”; SR^- is the fuzzy set “small value of sound realism assessment”; $AVAR$ is the average value of training scenarios diversity assessment. VAR^+ is the fuzzy set “high value of training scenarios diversity assessment”; VAR^- is the fuzzy set “small value of training scenarios diversity assessment”; DR_1, DR_2, …, DR_8 is the values of individual outputs of fuzzy rules.

In accordance with zero-order Sugeno algorithm, the following procedures are performed in the fuzzy inference process:

- Fuzzification;
- Aggregation;
- Activation;
- Defuzzification.

When performing the fuzzification procedure, the following values of the membership functions of the input variables to the fuzzy sets $IR^+(AIR)$, $IR^-(AIR)$, $SR^+(ASR)$, $SR^-(ASR)$, $VAR^+(AVAR)$ and $VAR^-(AVAR)$ are calculated in accordance with the expressions:

$$IR^-(AIR)=\begin{cases}1, & AIR \le IR_1^-;\\ \dfrac{IR_0^- - AIR}{IR_0^- - IR_1^-}, & IR_1^- < AIR < IR_0^-;\\ 0, & AIR \ge IR_0^-;\end{cases} \quad (1)$$

$$IR^+(AIR)=\begin{cases}0, & AIR \le IR_0^+;\\ \dfrac{AIR - IR_0^+}{IR_1^+ - IR_0^+}, & IR_0^+ < AIR < IR_1^+;\\ 1, & AIR \ge IR_1^+;\end{cases} \quad (2)$$

$$SR^-(ASR)=\begin{cases}1, & ASR \le SR_1^-;\\ \dfrac{SR_0^- - ASR}{SR_0^- - SR_1^-}, & SR_1^- < ASR < SR_0^-;\\ 0, & ASR \ge SR_0^-;\end{cases} \quad (3)$$

$$SR^+(ASR)=\begin{cases}0, & ASR \le SR_0^+;\\ \dfrac{ASR - SR_0^+}{SR_1^+ - SR_0^+}, & SR_0^+ < ASR < SR_1^+;\\ 1, & ASR \ge SR_1^+;\end{cases} \quad (4)$$

$$VAR^-(AVAR)=\begin{cases}1, & AVAR \le VAR_1^-;\\ \dfrac{VAR_0^- - AVAR}{VAR_0^- - VAR_1^-}, & VAR_1^- < AVAR < VAR_0^-;\\ 0, & AVAR \ge VAR_0^-;\end{cases} \quad (5)$$

$$VAR^+(AVAR)=\begin{cases}0, & AVAR \le VAR_0^+;\\ \dfrac{AVAR - VAR_0^+}{VAR_1^+ - VAR_0^+}, & VAR_0^+ < AVAR < VAR_1^+;\\ 1, & AVAR \ge VAR_1^+;\end{cases} \quad (6)$$

where IR_0^- and IR_1^- is the fuzzy set IR^- membership function parameters; IR_0^+ and IR_1^+ is the fuzzy set IR^+ membership function parameters; SR_0^- and SR_1^- is the fuzzy set SR^- membership function parameters; SR_0^+ and SR_1^+ – fuzzy set SR^+ membership function parameters; VAR_0^- and VAR_1^- is the fuzzy set VAR^- membership function parameters; VAR_0^+ and VAR_1^+ is the fuzzy set VAR^+ membership function parameters.

The aggregation procedure consists of estimating the degree of truth values G_1, G_2 … G_8 of fuzzy rules:

$$G_1 = IR^+(AIR) \wedge SR^+(ASR) \wedge VAR^+(AVAR), \quad (7)$$

$$G_2 = IR^+(AIR) \wedge SR^+(ASR) \wedge VAR^-(AVAR), \quad (8)$$

$$G_3 = IR^+(AIR) \wedge SR^-(ASR) \wedge VAR^+(AVAR), \quad (9)$$

$$G_4 = IR^+(AIR) \wedge SR^-(ASR) \wedge VAR^-(AVAR), \quad (10)$$

$$G_5 = IR^-(AIR) \wedge SR^+(ASR) \wedge VAR^+(AVAR), \quad (11)$$

$$G_6 = IR^-(AIR) \wedge SR^+(ASR) \wedge VAR^-(AVAR), \quad (12)$$

$$G_7 = IR^-(AIR) \wedge SR^-(ASR) \wedge VAR^+(AVAR), \quad (13)$$

$$G_8 = IR^-(AIR) \wedge SR^-(ASR) \wedge VAR^-(AVAR). \quad (14)$$

The activation procedure consists of calculating the numerator and denominator of the following expression:

$$VSI = \frac{\sum_{k=1}^{8} G_k DR_k}{\sum_{k=1}^{8} G_k}. \quad (10)$$

The defuzzification result is calculated by dividing the numerator by the denominator in expression (15).

As a result, the output of the created system receives the calculated value of the generalized indicator of the virtual simulator functioning.

So, in order to evaluate the performance of virtual simulators used for training in the diagnosis of Internet of Things networks, the following procedures are proposed:

1) The virtual simulator being evaluated is being studied by experts;
2) Each expert evaluates the image realism, sound realism, and variety of scenarios provided by the virtual simulator;
3) the grading results are fed to the input of the fuzzy inference system;
4) Fuzzification, aggregation, activation and defuzzification are performed during fuzzy inference, as a result of which the value of the generalized indicator of the functioning of the virtual simulator is evaluated.

The higher the value of the generalized indicator, the higher the resulting score of the virtual simulator.

3 EXPERIMENTAL STUDIES

Let's consider how a fuzzy inference system can be used to evaluate virtual simulators designed for diagnosis training of Internet of Things devices. The evaluated virtual simulator is studied by experts. Each expert then rates the visual realism, sound realism, and variety of scenarios provided by the virtual simulator. Scores for each parameter are averaged:

$$AIR = \frac{\sum_{j=1}^{J} IR_j}{J}, \quad (16)$$

$$ASR = \frac{\sum_{j=1}^{J} SR_j}{J}, \quad (17)$$

$$AVAR = \frac{\sum_{j=1}^{J} VAR_j}{J}, \quad (18)$$

where:

- J is the number of experts involved;
- IR_j is the assessment of the image realism given by an expert j;
- SR_j is the sound realism assessment given by an expert j;
- VAR_j is the scenarios diversity assessment given by expert j.

To conduct computational experiments to evaluate the characteristics of virtual simulators used in the field of IoT, a process model of estimating the characteristics of virtual simulators has been developed in the MATLAB software environment using the libraries of the Simulink package. The functional diagram of the model is presented in Figure 4.

The values AIR, ASR and $AVAR$ are calculated using the AIR_subsystem, ASR_subsystem and AVAR_subsystem, respectively, and are displayed by the virtual recorder Display_AIR_ASR_AVAR. Then the obtained values become the input of the Fuzzy Logic System.

The evaluation result is the value of the output VSI is a general indicator of the virtual simulator functioning. The value of the resulting indicator is displayed by the virtual recorder Display VSI.

Numerous computational experiments and real tests have shown that the estimated value of the virtual simulator VSI indicator correlates well with the PCD value is the probability of correctly diagnosing real IoT systems by those specialists who were trained on this virtual simulator.

Table 2 presents data that show how characteristics of 4 virtual simulators were assessed by 10 experts.

Using these data, the values AIR, ASR and $AVAR$ were calculated using formulas (16) – (18) applying AIR_ subsystem, ASR_ subsystem and AVAR_ subsystem. These values were entered to fuzzy inference system as input variables. Then, at the output of this system, the values of the generalized indicator of each virtual simulator functioning were obtained.

Then the probability of correct diagnosis of real IoT systems was assessed by experts who were trained on the studied virtual simulators. Data for probability estimation are presented in Table 3.

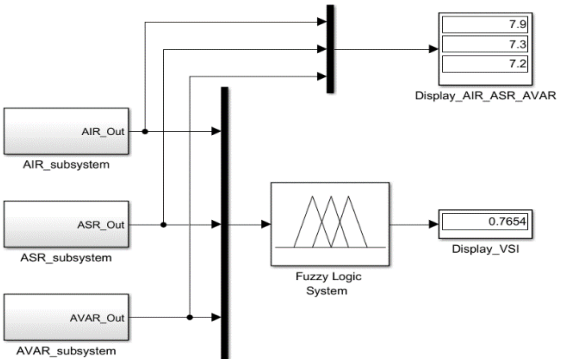


Figure 4: Functional diagram of the process software model of assessing the characteristics of virtual simulators used in the field of IoT.

The Table 3 contains values DR_{ix} that are the diagnosis results of IoT-system x by expert i, trained on a specific virtual simulator was calculated using the (19):

$$PCD = \frac{\sum_{i=1}^{I}\sum_{x=1}^{X} DR_{ix}}{I \cdot X}. \quad (19)$$

Diagrams were constructed based on the results of experiments and calculations. Figure 5 shows the VSI and PCD values obtained from a study of four different virtual simulators used for training in Internet of Things systems diagnosis.

Table 2: Experts' assessment of the virtual simulators' characteristics.

j	Evaluated virtual simulator											
	1			2			3			4		
	IR_j	SR_j	VAR_j	IR_j	SR_j	VAR_j	IR_j	SR_j	VAR_j	IR_j	SR_j	VAR_j
1	7	8	7	8	8	8	9	8	9	9	8	9
2	8	6	8	8	7	8	8	8	8	8	9	8
3	9	6	6	9	6	7	9	7	7	9	7	8
4	7	7	8	7	7	8	8	7	8	9	8	8
5	8	7	7	9	7	8	9	7	8	9	7	8
6	8	7	6	8	8	6	8	8	7	8	8	7
7	7	8	7	8	9	7	8	9	7	9	9	8
8	6	8	6	7	8	6	7	8	7	7	8	7
9	7	7	8	7	7	8	8	7	8	8	7	8
10	8	6	7	8	6	6	8	7	7	8	8	8

Table 3: Results of IoT systems diagnosis by experts trained on virtual simulators.

i	Virtual simulator used for training											
	1			2			3			4		
	The diagnosed IoT system, x			The diagnosed IoT system, x			The diagnosed IoT system, x			The diagnosed IoT system, x		
	1	2	3	1	2	3	1	2	3	1	2	3
1	1	1	0	1	1	1	0	1	1	1	1	1
2	0	1	1	1	1	0	1	1	1	1	1	0
3	1	0	0	1	1	1	1	1	0	1	1	1
4	1	0	1	1	0	0	1	1	1	1	0	1
5	1	1	1	0	1	1	1	1	0	1	1	1
6	0	1	1	1	1	0	1	0	1	1	0	1
7	1	0	1	1	1	1	1	1	0	1	1	1
8	1	1	0	1	0	1	1	1	1	1	1	0
9	1	0	1	1	1	1	1	0	1	0	1	1
10	1	1	0	1	0	1	1	1	1	1	1	1

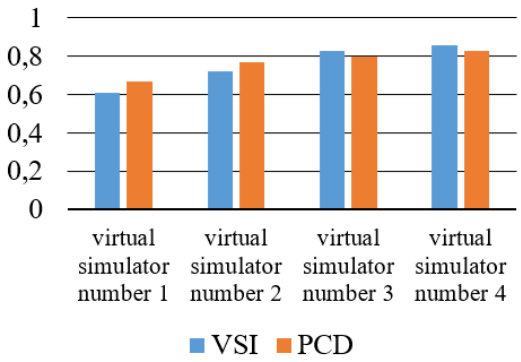


Figure 5: Diagrams of VSI and PCD values obtained from the study of four different virtual simulators.

Figure 5 shows that the higher the generalized indicator values of the virtual simulator, the greater the probability of correct IoT systems diagnosis by those experts who trained on it. Thus, the proposed fuzzy inference system can be recommended for on one of the simulators. The probability of correct diagnosis of real IoT systems by experts who were assessing the virtual simulators characteristics that are intended for training in Internet of Things systems diagnosis.

The value of the results obtained in comparison with the results of other modern studies lies in the fact that the proposed system makes it possible to evaluate the value of a generalized indicator that takes into account the most important criteria for the functioning of virtual simulators. It should also be noted that the quality of the fuzzy inference system settings depends on the number of experts involved. This can be attributed to the limitations of the proposed development.

3 CONCLUSIONS

The goal of the study was achieved, namely, a fuzzy logical inference system was developed that allows for improving the process of assessing the virtual simulators characteristics used for training in Internet of Things systems diagnosis.

The following results were obtained in the work:

1) An analysis of capabilities and specifics of the virtual simulators functioning used for training in Internet of Things systems diagnosis was carried out. The analysis showed that developers offer various options for virtual simulators that allow to train the diagnosing of IoT systems. To select devices with the best characteristics, as well as to identify shortcomings and improve virtual simulators, tools for assessing characteristics are used.
2) As indicators for assessing the characteristics of virtual simulators used for training in IoT systems diagnosis, it is proposed to use indicators of image realism, sound realism and training scenarios sets diversity, as well as a general indicator of the virtual simulator functioning. Scores for the first three indicators are given by experts in points from 1 (lowest score) to 10 (highest score). The values of the general indicator of the virtual simulator functioning should adequately take into account the values of the particular indicators of image realism, sound realism and the training scenarios sets diversity provided by the virtual simulator.
3) An assessment system has been developed for the characteristics of virtual simulators intended for training in IoT systems diagnosis. It is based on the use of fuzzy logical inference. The parameters of the membership functions of fuzzy sets and individual outputs of fuzzy rules were automatically selected using a neural network setup. The average values of assessments of image realism, sound realism, and the variety of training scenarios are fed to the input of the fuzzy logical inference system. Fuzzy inference procedures (fuzzification, aggregation, activation, and defuzzification) are then performed using these values. As a result, the desired value of the generalized indicator of the virtual simulator functioning is recorded at the output of the fuzzy logical inference system.
4) In order to study the proposed fuzzy logical inference system in the MATLAB software environment using the libraries of the Simulink package, a model of the process of assessing the characteristics of virtual simulators intended for training in diagnosing IoT systems has been developed. Numerous computational experiments have been carried out using this software model. A comparison of their results with the results of real IoT systems diagnosing showed that the higher the values of the generalized indicator of the virtual simulator functioning, the greater the probability of correct IoT systems diagnosis by the experts who trained on it. This confirms the feasibility of using the developed fuzzy logical inference system to evaluate the characteristics of virtual simulators used to IoT systems diagnosis.

The results obtained can be recommended for use in companies that develop and improve virtual simulators designed for educational purposes. The proposed development can be used as the basis for creating software for evaluating the usefulness of virtual simulators created for training in the correct diagnosis of the technical condition of Internet of Things systems.

Future work will focus on developing tools for evaluating the performance of virtual simulators used to teach IoT network management.

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The Role of Silver Nanoparticles in Enhancing the Structural and Antibacterial Properties of Chitosan/PEO Blend Films

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Keywords: Chitosan, Polyethylene Oxide, Silver Nanoparticles, Nanocomposites, Antibacterial Activity.

Abstract: The current study investigates the enhancement of the structural, morphological, and antibacterial properties of a nanocomposite material composed of chitosan (CS) and polyethylene oxide (PEO). The improvement is achieved through the incorporation of silver nanoparticles (AgNPs) at varying concentrations of 1%, 3%, and 5%. A variety of analytical techniques were applied. The XRD, FE-SEM, and FTIR investigations revealed that the introduction of AgNPs induced substantial alterations in the crystallinity of the material, the characteristics of its surface, and the behavior of functional groups within the polymer matrix. The changes observed in these parameters underscore the influence of AgNPs on the fundamental properties of the CS/PEO blend. To further characterize the nanocomposites, Zeta Potential analysis was performed. This technique provides important information about the stability and surface charge characteristics of the nanocomposites, which in turn allows for a better understanding of the dispersion and distribution of nanoparticles within the polymer matrix. Antibacterial tests demonstrated enhanced inhibition against Staphylococcus aureus and Escherichia coli, particularly in AgNP-containing films. The combined effects of chitosan and AgNPs contributed to strong antibacterial performance, especially against Gram-positive bacteria.

1 INTRODUCTION

Material science benefits greatly from nanotechnology since it allows scientists to alter polymer characteristics for creating new materials. The ratio between surface area and volume makes nanotechnology-based composites both thermally and electrically stable which makes them more efficient at reduced cost [1], [2]. Multiple studies explore nanocomposites that use synthetic polymers combined with metal oxide and carbon filler nanomaterials for enhancing multiple functional properties [3], [4].

Chitosan obtains its nature as a biodegradable biocompatible polymer from chitin through deacetylation. The many functional groups in chitosan strengthen structure while enhancing biological functions which results in its efficient antimicrobial properties. The medical sector frequently employs chitosan as an effective material because this compound achieves low toxicity alongside its capability to develop films and hydrogels and nanoparticles [5]-[10].

The properties of chitosan nanoparticles (CNPs) become more useful for biomedical and environmental applications because they show improved biocompatibility together with antimicrobial activity and membrane penetration capabilities [11]-[13]. PEO features versatility as a stretchable non-toxic substance because it dissolves well in water through hydrogen bond interactions that unite with chitosan into a single homogeneous material that demonstrates better physicochemical behavior. PEO demonstrates ideal properties for medical uses because it matches human tissue composition so it finds applications in wound dressing and drug delivery systems [5], [14]. The casting method functions as a common approach to develop nanocomposite systems which exhibit improved structural and optical properties [15]. Nanotechnology integration into polymers resulted in the development of nanocomposites that boost biomedical materials' properties and support complex medical applications [16]. The materials achieve outstanding properties regarding mechanical performance combined with strength and durability alongside wear resistance characteristics thus providing high effectiveness for medical implementations and engineering applications [2], [17] and [18]. Additionally, several polymer blends have shown antibacterial potential when reinforced with metal oxide or silver nanoparticles [19]. Among

nanomaterials, metallic nanoparticles (1-100 nm) possess unique physical and chemical properties, such as high catalytic activity, making them valuable in research on microbial resistance to antibiotics [20], [21]. Silver, copper, and zinc are commonly used as antimicrobial agents, with studies showing that silver nanoparticles (AgNPs) demonstrate the highest effectiveness against Streptococcus mutans [22]. Additionally, AgNPs exhibit strong antimicrobial activity against bacteria, fungi, and viruses, renewing interest in their medical applications, particularly against resistant strains [23].

This study investigates the structural and antibacterial properties of chitosan/PEO nanocomposite films reinforced with silver nanoparticles. XRD, FE-SEM, AFM, FTIR, EDX, zeta potential analysis, and antibacterial testing were employed to assess the impact of AgNP concentration to emphasize their potential for biomedical applications.

2 EXPERIMENTAL WORK

2.1 Materials

Chitosan (≥90% purity, 30–50 nm) was obtained from Nanochemazone, Polyethylene oxide (PEO) (Mw = 3,000,000 g/mol, ≥98% purity) was purchased from Cheng Du Micxy Chemical Co., Ltd., and silver nanoparticles (AgNPs) (10–20 nm, ≥99.9% purity) were supplied by Sky Spring Nanomaterials. Acetic acid (≥99.7% purity) was used as a solvent and deionized distilled water to ensure the purity of the sample.

AFM test was conducted to analyze the initial surface morphology and roughness of the raw materials, which include chitosan, polyethylene oxide (PEO), and silver nanoparticles (AgNPs). Measurements were performed at a scan size of 2.0 × 0.2 µm. Table 1 indicates that the PEO powder demonstrated the greatest surface roughness (Rq = 25.72 nm), signifying a markedly uneven structure. Conversely, chitosan powder exhibited a more uniform shape (Rq = 19.91 nm). AgNPs demonstrated the lowest Rq value (12.78 nm), indicating their nanometric scale and reasonably uniform distribution, as illustrated in Figure 1. The average particle sizes determined via AFM line analysis were 48.18 nm for chitosan, 78.88 nm for PEO and 38.87 nm for AgNPs, thereby affirming the nanoscale characteristics of the materials.

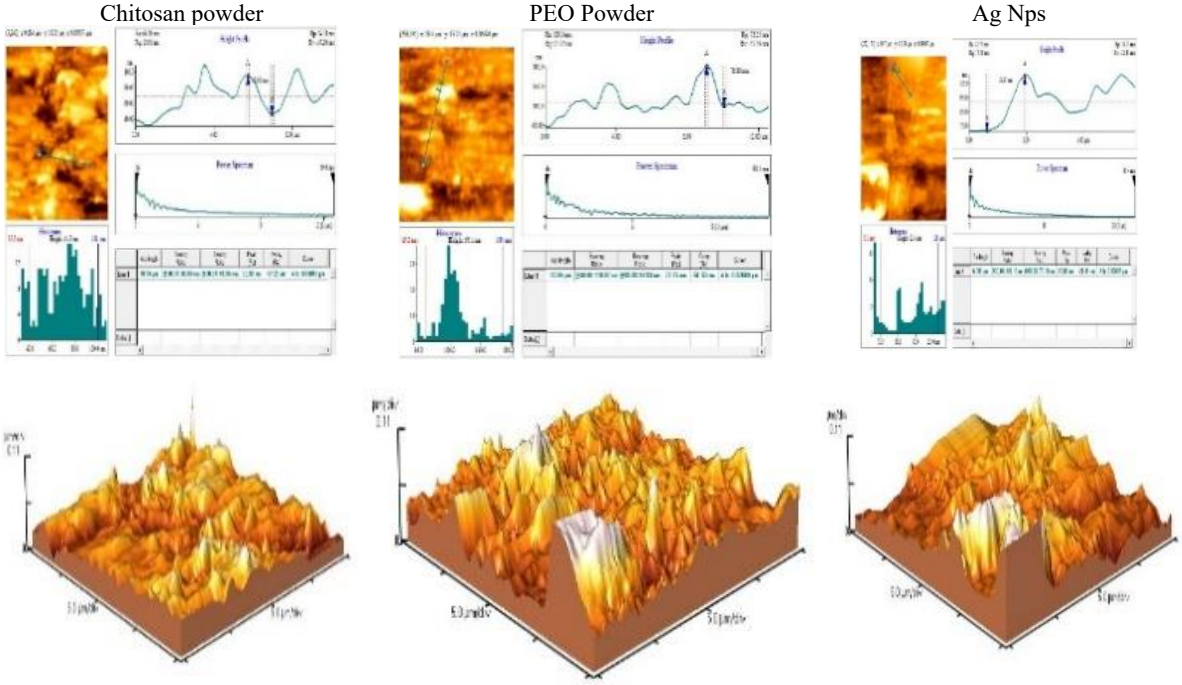


Figure 1: AFM images of chitosan, PEO, and AgNPs powders at 2.0 µm/div magnification.

Table 1. AFM roughness parameters and average particle sizes of raw materials:

Sample	Rq (nm)	Rp (nm)	Rv (nm)	Max Height (nm)	Average Particle Size (nm)
Chitosan	19.91	39.38	-37.20	61.3	48.18
PEO	25.72	72.25	-51.59	99.1	78.88
AgNPs	12.78	19.03	-21.41	32.4	38.87

2.2 Methods of Preparation

The chitosan/polyethylene oxide (Cs/PEO) composite augmented with silver nanoparticles (AgNPs) was synthesized via the solution casting technique. One gram of chitosan was dissolved in 100 milliliters of 1% acetic acid and agitated at 300 revolutions per minute for six hours at ambient temperature. PEO (1 g) was independently dissolved in 100 mL of distilled water at 50°C. The PEO solution was incrementally incorporated into the chitosan solution while maintaining continuous agitation until a uniform mixture was achieved. Silver nanoparticles (AgNPs) were integrated at concentrations of 1%, 3%, and 5%, thereafter subjected to ultrasonic treatment (120 W, 1 hour) to guarantee uniform dispersion. The finished solution was deposited into 14 cm Petri plates and desiccated at ambient temperature for 5 days; the preparation methods are illustrated in Figure 2.

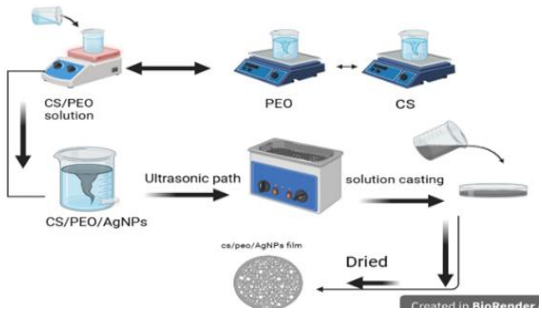


Figure 2: Schematic representation of the preparation process of chitosan/PEO/AgNPs nanocomposite films.

2.2.1 Characterization Techniques

Structural, and morphological, properties were analyzed using multiple techniques such as XRD (Philips XPERT-PRO) to determine crystallinity and phase composition (Cu-Kα, 10°–80°), EDX confirmed elemental composition, and the presence of AgNPs, FTIR (Shimadzu IR Affinity) was used to identify functional groups in the range of 4000–400 cm^{-1}, Zeta Potential measurements (Horiba SZ-100) were conducted to evaluate the surface charge and colloidal stability at 25°C, The agar disk diffusion was used to identify the antibacterial activity against S. aureus and E. coli. The tested sample was loaded on the well, and bacterial cultures were placed on Mueller-Hinton agar plate. Measurement of inhibition zones was done after a 24 hours incubation at 37 o C. Distilled as the negative control water was used.

3 RESULTS AND DISCUSSION

3.1 XRD Analysis

Figure 3 displays the XRD patterns of chitosan (Cs) (S1), polyethylene oxide (PEO) (S2), Cs/PEO mix (S3), and Cs/PEO combined with varying concentrations (1, 3, 5) % of silver nanoparticles (AgNPs) (S4, S5, S6) accordingly. The diffraction peaks at 2θ = 10.5° and 20.1° signify an orthorhombic structure, with supplementary peaks corroborating the semi crystalline characteristics of chitosan [24]-[26]. In contrast, PEO had specific peaks at 2θ = 19.2°, 21.0°, 23.3°, and 26.3°, signifying its monoclinic crystalline structure, accompanied by smaller peaks at 27.1° [27]. The XRD pattern of the Cs/PEO blend exhibited peaks from both constituents, hence affirming effective synthesis. The peak at 2θ = 23.1°, linked to PEO, diminished in intensity and widened, signifying hydrogen bonding interactions between Cs and PEO [28]. The crystallite size (D) for the (111) peak was determined using the Debye-Scherrer equation [29] ($D=K\lambda/\beta \cos\theta$), where K is a constant (0.91), λ represents the X-ray wavelength (0.154 nm), β denotes the full width at half maximum (FWHM), and θ signifies the diffraction angle. The mean crystallite size of AgNPs rose from 15.8 nm (S4) to 21.6 nm (S5) and 25.7 nm (S6), signifying improved crystallization with increased AgNP concentrations, and a decrease in FWHM from 0.52° to 0.32°. The peak at 2θ = 32.004° indicates potential surface crystallization on AgNPs resulting from polymer-nanoparticle interactions, a process documented in prior nanocomposite research [30].

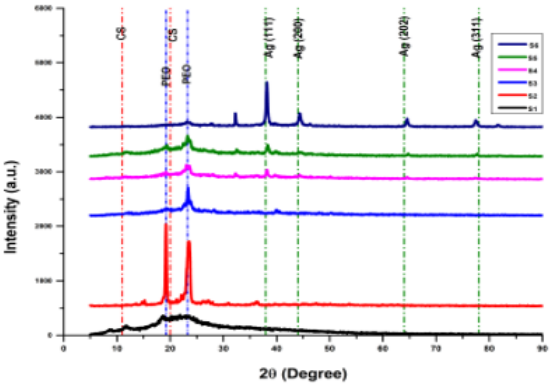


Figure 3: XRD patterns of all samples, including pure chitosan, pure PEO, chitosan/PEO blend, and chitosan/PEO blend with 1%, 3%, and 5% AgNPS.

3.2 FTIR Analysis

Figure 4 presents the FTIR spectra of chitosan (Cs), PEO, their blend (Cs/PEO), and Cs/PEO reinforced with different AgNP concentrations.

In the chitosan spectrum, a broad peak at 3360–3285 cm^{-1} corresponds to –OH and –NH stretching vibrations, indicating strong hydrogen bonding. Peaks at 1645 cm^{-1} (C=O) and 1534 cm^{-1} (N–H) confirm the presence of amide structures [25], [31].

The PEO spectrum exhibits a strong absorption peak at 1094 cm^{-1}, attributed to C–O–C ether stretching, along with weak absorptions around 2872 cm^{-1}, corresponding to C–H stretching vibrations, characteristic of PEO [26]. In the Cs/PEO blend, a slight shift and intensity reduction of the 3360–3285 cm^{-1} band indicates hydrogen bond formation between chitosan and PEO. Additionally, peaks at 1645.95 cm^{-1} (NH) and 1119.48 cm^{-1} (C–O–C) confirm structural interactions within the blend [1].

Upon silver incorporation (S3–S6), spectral changes were observed, particularly in the 4000–1000 cm^{-1} range. While the 4000–3000 cm^{-1} region remained stable, the 3000–1500 cm^{-1} range showed variations in C–H (2900 cm^{-1}) and C=O (1650 cm^{-1}) peaks, indicating silver interactions. The most significant changes occurred in the fingerprint region (1500–1000 cm^{-1}), where increased silver content enhanced C–O (1000–1200 cm^{-1}) intensity, suggesting direct interactions with oxygen-containing groups. The results suggest that silver modifies the molecular structure by interacting with oxygen-containing groups while maintaining the composite's fundamental structure, consistent with previous studies like Mahmoud et al. (2019) [19], [32].

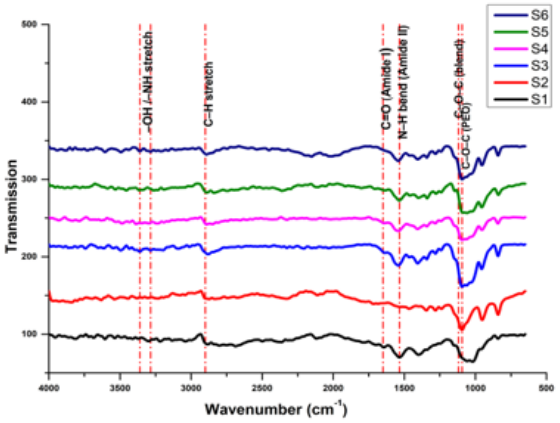


Figure 4: FTIR spectra of all samples, including pure chitosan, pure PEO, chitosan/PEO blend, and chitosan/PEO blend with 1%, 3%, and 5% AgNPS, showing the characteristic functional groups and interactions.

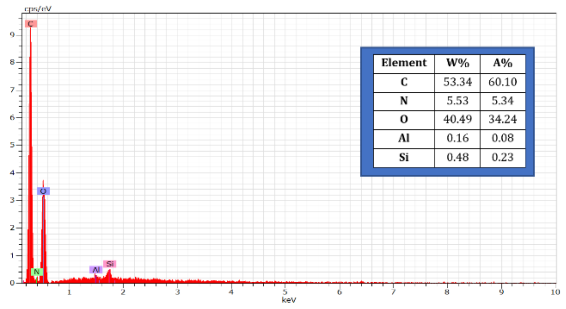
3.3 Energy Dispersive X-Ray Spectroscopy (EDX) Results

The elemental composition of the polymeric samples was analyzed using energy-dispersive X-ray Spectroscopy (EDX) to identify the presence of key elements and confirm the structural integrity of the prepared composites.

The EDX spectrum of S1 (Fig. 5), representing pure chitosan, confirmed its organic nature as it primarily consists of carbon (C) and oxygen (O). This composition aligns with the well-documented molecular structure of chitosan, which mainly consists of polysaccharide chains containing carbon, oxygen, and nitrogen [33].

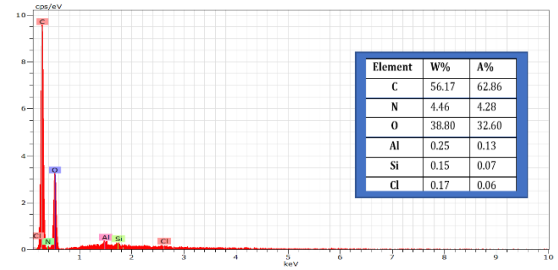
In addition, trace amounts of aluminum (Al) and silicon (Si) were detected, likely originating from the natural mineral content in crustacean shells used as raw material. Previous studies have reported the persistence of these elements despite the demineralization steps during preparation [34].

In sample S3 Figure 6, characterized by an equal mixture of chitosan and PEO, EDX analysis indicated elevated concentrations of carbon (56.17%) and oxygen (38.80%), underscoring the organic composition of the polymeric structure. Nitrogen is derived from chitosan, whereas the oxygen concentration is indicative of both components' contributions. A minimal quantity of chlorine was also identified, presumably due to the processing procedure. The results demonstrate the effective amalgamation of both polymers and the establishment of a stable composite structure.



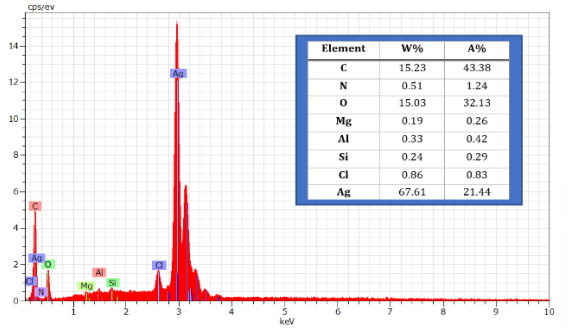
Element	W%	A%
C	53.34	60.10
N	5.53	5.34
O	40.49	34.24
Al	0.16	0.08
Si	0.48	0.23

Figure 5: EDX spectrum and elemental composition of S1 (Cs).



Element	W%	A%
C	56.17	62.86
N	4.46	4.28
O	38.80	32.60
Al	0.25	0.13
Si	0.15	0.07
Cl	0.17	0.06

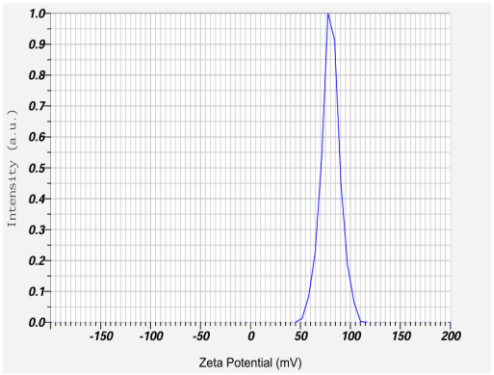
Figure 6: EDX spectrum and elemental composition of S3 (chitosan/PEO blend).



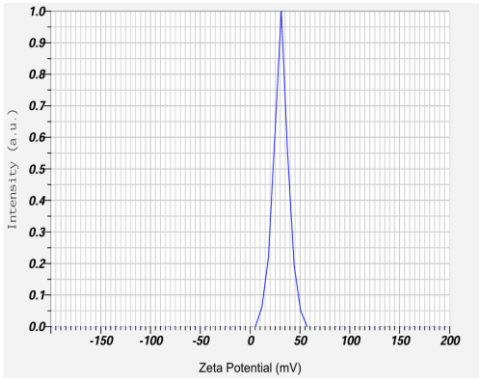
Element	W%	A%
C	15.23	43.38
N	0.51	1.24
O	15.03	32.13
Mg	0.19	0.26
Al	0.33	0.42
Si	0.24	0.29
Cl	0.86	0.83
Ag	67.61	21.44

Figure 7: EDX spectrum and elemental composition of S6 (chitosan/PEO blend with 5% AgNP.

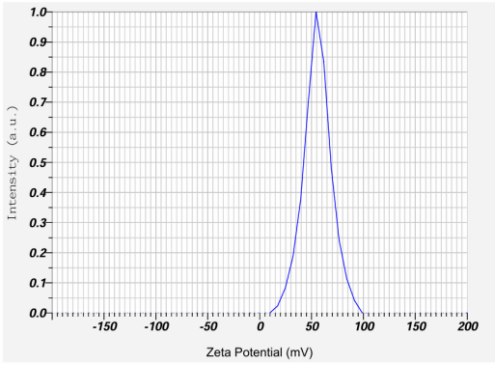
EDX analysis of sample S6 Figure 7 confirmed the presence of silver at 7.52 wt%, indicating the successful incorporation of silver nanoparticles into the polymer matrix. The carbon and oxygen contents remained stable, suggesting that the polymer structure was not significantly affected. The nitrogen content (3.96%) was within the expected range.



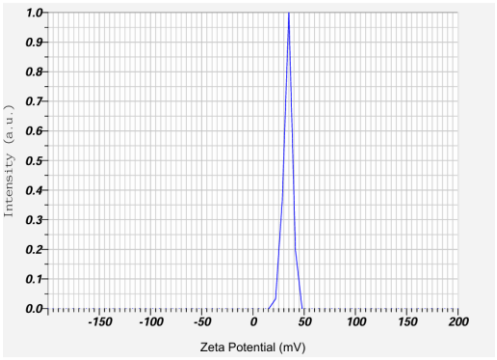
S1



S2



S3



S6

Figure 8: Zeta potential curves of the selected samples (S1, S2, S3, and S6).

3.4 Zeta Potential Analysis

The surface charge of the prepared films was evaluated using Zeta Potential measurements at 25 °C using a Horiba SZ-100 as in Table 2 and Figure 8.

The chitosan membrane (S1) exhibited a high positive Zeta Potential of 80.2 mV, attributed to the protonation of amino groups, indicating excellent stability in acidic environments [35]. In contrast, the PEO film (S2) showed a significantly lower value (30.8 mV), consistent with its neutral chemical nature and known tendency to screen surface charges, thereby reducing electrostatic interactions [36].

Table 2: Zeta Potential values of the selected membrane samples.

Samples	Zeta Potential (Mv)
S1	80.2
S2	30.8
S3	55.7
S6	34.0

The CS/PEO blend (S3) showed an intermediate value (55.7 mV), suggesting enhanced intermolecular interaction and partial retention of chitosan's surface charge. This can be attributed to hydrogen bonding between –NH and –OH groups of chitosan and the ether oxygen in PEO [28].The nanocomposite film containing 5% AgNPs (S6) exhibited a reduced Zeta Potential (34.0 mV), which may be attributed to nanoparticle agglomeration or surface charge masking by the polymer matrix. This observation agrees with previous reports suggesting that at higher AgNP concentrations, particles tend to aggregate, reducing the active surface area and weakening electrostatic interactions [37], [38].

Despite the lower surface charge, it is reported that chitosan-AgNPs systems can retain some positive charge due to protonated amino groups, which contributes to their antibacterial potential [39].

3.5 Antibacterial Activity Analysis

The antibacterial properties of the chitosan/PEO-AgNPs solution were evaluated using the agar well diffusion method, showing a concentration-dependent effect. According to Table 3, inhibition zones ranged from 6.5 mm (lowest concentration) to 26 mm (highest concentration), confirming their effectiveness.

When tested against Staphylococcus aureus, S6 exhibited the highest antibacterial activity, with an inhibition zone of 26 mm at 100% concentration, consistent with previous findings reporting that Cs/Ag NPs maintain strong antibacterial effects even at low concentrations [40]. S3, S4, and S5 also showed inhibition zones exceeding 23 mm, reinforcing the bactericidal effect of silver incorporation Figure 9.

Table 3: Antibacterial activity of chitosan/PEO nanocomposite solution against Staphylococcus aureus (Gram-positive) and Escherichia coli (Gram-negative) bacteria, represented by the inhibition zone (mm) at different concentrations.

Samples		A control	B 12.5%	C 25%	D 50%	E 100%
S.aures	S 1	6	6.5	11	14.5	19
	S 2	6	8.6	12.7	14	17
	S 3	6	8	9	20.9	23.7
	S 4	6	7	12	19.5	24
	S 5	6	11	16	21	23
	S 6	6	8.5	10	20	26
E. coli	S 1	6	9	12	14	18
	S 2	6	11	12	13	17
	S 3	6	10.5	14	15	18
	S 4	6	8	13	17	20
	S 5	6	9	9.5	16	22
	S 6	6	8	11	17	21

Against Escherichia coli, antibacterial efficacy was lower, with S5 showing the highest inhibition zone (22 mm at 100%), likely due to the outer membrane barrier of Gram-negative bacteria, which limits nanoparticle penetration, as previously reported Figure 10 [41], [42].

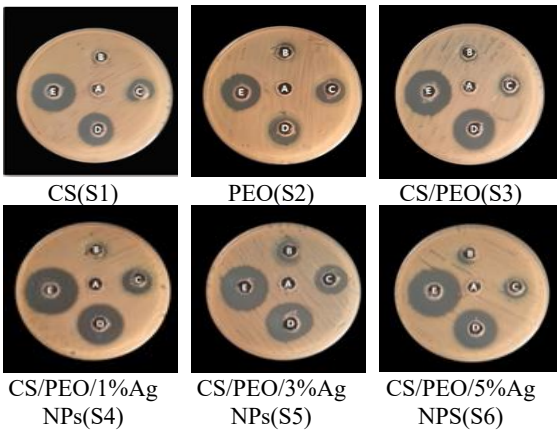


Figure 9: Antibacterial activity of chitosan, PEO, and chitosan/PEO nanocomposite films with different silver nanoparticle concentrations against Gram-positive Staphylococcus aureus bacteria, showing the inhibition zones for each sample.

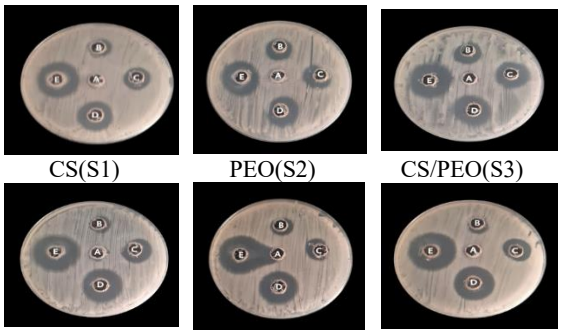


Figure 10: Antibacterial activity of chitosan, PEO, and chitosan/PEO nanocomposite films with different silver nanoparticle concentrations against Gram-negative Escherichia coli bacteria, showing the inhibition zones for each sample.

The observed antibacterial properties a direct correlation was observed between silver concentration and inhibition zone size, with increased silver content enhancing bacterial inhibition, as confirmed by previous studies reporting that higher silver content promotes antimicrobial ion release [40], [41].

The potential of silver-based nanocomposites has been confirmed, particularly against Gram-positive bacteria, while further modifications are still required to improve their efficacy against E. coli. The importance of continued research on long-term stability and interactions in medical applications has also been highlighted in previous studies [40], [43].

4 CONCLUSIONS

Incorporating silver nanoparticles (AgNPs) into the chitosan/PEO composite improved their structural integrity and antibacterial efficacy. XRD analysis confirmed the semi-crystalline nature of the blend and verified AgNPs incorporation through distinct diffraction peaks, including those corresponding to silver, while EDX verified silver presence and increasing Ag content with concentration. FTIR revealed strong chitosan-PEO hydrogen bonding, with spectral shifts indicating AgNP-polymer interactions. With spectral shifts indicating chemical interactions between AgNPs and polymer. Zeta potential analysis demonstrated significant variations in surface charge, reflecting changes in colloidal stability and electrostatic interactions due to AgNPs addition, where Antibacterial activity shows improved inhibition zones against Staphylococcus aureus and E. coli, with stronger effects on Gram-positive bacteria, confirming the synergistic antimicrobial effect of chitosan and AgNPs. The antibacterial response depended on both concentration and strain. S6 (5% AgNPs) demonstrated the most potent suppression of Staphylococcus aureus, while S5 (3% AgNPs) exhibited the greatest antibacterial efficacy against Escherichia coli. The results indicate that AgNP-reinforced CS/PEO composites are viable options for biomedical applications, including antimicrobial wound dressings. Future investigations must prioritize the assessment of long-term stability, cytotoxicity, and in vivo biocompatibility for clinical application.

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An IT-Guided Design of Smart Bio-Nanocomposite Films for Next-Generation Antimicrobial Wound

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Abstract: In recent years, electrospinning has gained significant attention for the production of innovative nanofibrous materials with diverse applications in science and engineering. The use of graphene oxide and natural products derived from plants and/or trees has gained remarkable popularity in many scientific disciplines due to their availability, eco-friendliness, and unique properties. In this study, an approach is presented for producing nanofibers using a carefully prepared mixture of 2 wt% Gum Arabic (GA), a natural tree gum extract, 8 wt% Polyvinyl alcohol (PVA), an environmentally friendly stabilizer, and 0.5 wt% Graphene Oxide (GO), which was incorporated to enhance the durability and performance of the fabricated nanofibers. The electrospinning process was carried out using a laboratory-made electrospinning system under controlled conditions. X-ray diffraction (XRD) and field emission scanning electron microscope (FESEM) analysis were employed to characterize the GO. Furthermore, FESEM was also utilized to investigate the morphology, distribution, and diameters of the nanocomposite fibers.

1 INTRODUCTION

In recent years, electrospinning has become a widely recognized method for fabricating polymer nanofibers with adjustable diameters and morphologies through the regulation of processing and solution variables. Consequently, electrospinning has been extensively employed as an effective technique for fabricating composite nanofibers [1]. Moreover, the design versatility and component controllability of electrospun nanofibers are considerable advantages. Due to the superior characteristics derived from these structural benefits, electrospun nanofibers possess significant potential for extensive application in protective textiles, filtration, composite reinforcement, and biomedical fields, including tissue engineering scaffolds, wound dressings, and drug delivery systems [2].

Nanomaterials have demonstrated excellent properties that surpass those of bulk materials in various fields [3] - [6]. One of the most interesting materials is graphene oxide (GO). It has recently been regarded as an essential material in the domain of carbon nanostructures. GO resembles graphene, with the hexagonal planes of graphene adorned by oxygen atoms. The presence of oxygen-containing functional groups (hydroxyl, epoxy, and carboxyl) on the GO surface makes it more hydrophilic and easier to spread in water and other polar solvents. The remarkable chemical and physical features of GO render it highly effective in catalysis [7], [8], energy [9], and drug delivery [10], as well as numerous further applications [11] - [15].

The polydispersity of the graphene/polymer solution before the electrospinning process is a critical component in the manufacturing of graphene-based nanofibers. Numerous materials have been evaluated as co-blending solutions for nanofiber manufacturing [16]; Nonetheless, there exists a significant deficiency in the utilization of "green" polymers (for instance, tree-derived gums [17], [18]) for this purpose. This can render the entire process more sustainable and cost-effective. Consequently, we have endeavored to close this gap by utilizing GA as a renewable, eco-friendly, biodegradable agent for the synthesis of graphene-based nanofibers. GA or Acacia gum is the exudate from the Acacia Senegal and Acacia seyal trees, which are part of the Leguminosae family. It is a complex, branching heteropolysaccharide, either neutral or somewhat acidic, and composed of 1, 3-linked β-D-galactopyranosyl units. L-arabinose, L-rhamnose, and D-glucuronic Acids have also been identified as

components of this polymer [19]. The side chains consist of two to five 1, 3-linked β-D-galactopyranosyl units that connect to the primary chain through 1, 6-linkages [20]. Historically, PVA has proven to be a superior co-solvent in gum solutions for the electrospinning process, markedly outperforming PEO (polyethylene oxide) [21]. Despite substantial research on electrospun polymer and polymer/graphene-based nanofibers, controlling fiber continuity and morphology while preserving environmental sustainability is still a challenge. Many biopolymers show poor mechanical stability or restricted spinning ability, which limits their practical application.

In the present study, a ternary PVA/GA/GO composite system is constructed in which each component serves a specific function. The PVA is selected as the main matrix due to its superior electrospinning ability, mechanical stability, and water solubility [22]. The GA, a naturally occurring and biodegradable polysaccharide, is used as a green modifier to improve intermolecular interactions and solution viscosity; nevertheless, when used alone, its high molecular complexity may have a negative impact on jet stability. It must add to synathic polymer to produce fibers [23]. Incorporating the GO as an electrically conductive and nanoscale reinforcing filler enhances the mechanical properties of fibers and modifies optical properties [24]. The purpose of this work is to understand how fiber production and optical behavior in electrospun nanofibers are influenced by the synergistic combination of PVA, GA, and GO.

2 EXPERIMENTAL PART

2.1 Materials

All chemicals used in this study were of analytical grade. Polyvinyl alcohol molecular formula (C4H6O2C2H4O)X, 67000 g/mol molecular weight, 1400 degree of polymerization, 88% degree of hydrolysis, viscosity of 8 mPa.s (in 4% aqueous solution), and physical form pure, solid, white, odorless, granular. It was purchased from ME Scientific Engineering Ltd. GA was purchased from THOMAS BAKER, India, with maximum impurity limits: acid-insoluble ash of 1.0%, water-insoluble matter of 1.0%, loss of 15.0% on drying at 105 °C, and 5.0% sulfated ash. GO was purchased from Platonic Nano Private Limited, India, with a purity of 98%, APS (Average Particle Size) of 20 nm, and a thickness of less than 5 nm.

2.2. Preparation of PVA/GA/GO Solutions

In the first step, a PVA solution was prepared by adding 1 gram of PVA polymer to 10 ml of deionized water and homogenizing the solution at 80 °C with continuous stirring for 60 minutes.

In the second stage, a PVA-GA solution was prepared by adding 0.8 grams of the synthetic polymer PVA in 10 ml of deionized water and mixing them as in the first step under continuous stirring at a temperature of 80 °C for 60 minutes. Then, 0.2 grams of GA was added to the solution and left to homogenize overnight under continuous stirring.

In the final stage of preparation, a GO solution was prepared by dissolving 0.05 grams of graphene oxide in 10 ml of deionized water. This mixture was ultrasonicated for 70 minutes to achieve a fine and even consistency. After the dispersion process was completed, the solution was transferred to a magnetic mixing device, where 0.8 grams of PVA were added to the mixture. The mixing process continued for 90 minutes at 80 °C to ensure complete dissolution and homogeneity of the polymer. Then, 0.2 grams of GA were added to the mixture, with continuous magnetic stirring overnight to ensure optimal homogeneity and achieve the desired physical and chemical properties of the resulting solution.

2.3 Electrospinning Process

A laboratory-scale electrospinning system was used to produce nanofibers. This system includes a high-voltage power supply (HVPS) capable of delivering up to 30,000 V with integrated voltage measurement, an acrylic injection pump with Bluetooth connectivity for wireless control and Arduino-based modification, and an aluminum sheet accumulator to ensure electrical conductivity. Two electronic circuits manage the HVPS and injection pump, providing operational precision and adaptability.

Prepared solutions were loaded into a 5 ml syringe within our lab-built electrospinning system. This system comprises a smart syringe pump, a high-voltage power supply, and a collector. Electrospinning was performed with a 16 cm needle-collector distance, a 30 kV voltage, and a 0.02 ml/min flow rate.

2.4 Characterization

XRD (Shimadzu-6000, Japan; 1.2 kW; Cu) with a wavelength of 1.5406 Å was used for the characterization of GO.

The morphology of the prepared nanofibers was observed using a FESEM (Nova NanoSEM 450, FEI, USA, and Axia ChemiSEM, Thermo Fisher Scientific, USA, and TESCAN Vega2, Czech Republic). Before analysis, the samples were sputter-coated with gold to improve conductivity during imaging. To determine the average diameters and diameter distribution of the prepared nanofibers, 40 different fibers were randomly selected, and their diameters were measured using ImageJ software.

A UV-visible spectrometer (DU-8800, DRAWELL, China) was used to study the optical properties of the prepared samples.

3 RESULTS AND DISCUSSION

3.1 XRD and FESEM Analysis of GO

GO was analyzed via XRD and FESEM, as depicted in Figure 1. The XRD pattern reveals significant peaks, notably at 10°, associated with the (001) plane, reflecting interlayer spacing attributed to oxygen functionalities [25]. Conversely, the weak peak at 42° pertains to a short-range order inside the layers of stacked graphene, which are characteristic of the semicrystalline profile of the turbostratic graphite structure [26] - [29]. The FESEM image of GO reveals a broad surface and an intricate sheet with a smooth morphology. The GO appears to be thin, transparent, crumpled layers with notable overlapping regions and folded edges. The visible wrinkles and ripples could indicate that the sheets of graphene oxide have a few layers. The edges of the GO sheets are clear and display the thin nature of the material.

3.2 UV-Visible Spectrum

The optical properties of the prepared solutions of PVA, PVA/GA, and PVA/GA/GO were studied using a UV-visible spectrometer. The spectrum exhibits a distinct absorption within the 200-300 nm band, as shown in Figure 2a. No significant absorption occurs above 300 nm, signifying an absence of robust optical response in the visible band. This verifies that PVA alone does not substantially enhance absorption at elevated wavelengths; this demonstrates that PVA alone has limited optical absorption in the visible region. It was seen that pronounced absorption peaks in the range of 200-300 nm, akin to the PVA spectra, albeit with alterations attributable to the influence of GA, see Figure 2b. Nevertheless, there is no notable alteration beyond 300 nm, suggesting that the incorporation of GA did not substantially enhance the optical responsiveness of the solution.

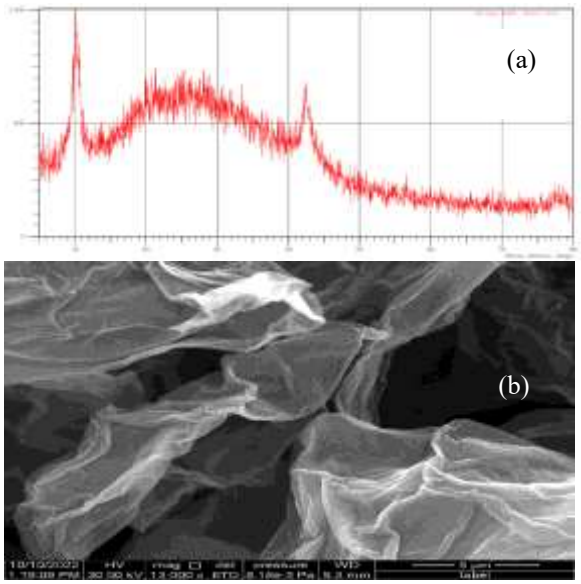


Figure 1: GO characterization: a) XRD analysis of GO and b) FESEM.

Although GA does not considerably widen the absorption range, it may alter other material properties that were not examined in this study. The incorporation of GO results in a notable alteration in the spectrum, as shown in Figure 2c. A notable rise in absorption is observed beyond 250 nm, succeeded by the appearance of a wide absorption band that extends to 400 nm and beyond. This illustrates the characteristics of optical transitions in GO, noted for its significant absorption in ultraviolet and visible light. In contrast to the two preceding solutions, it is evident that GO is the principal element influencing this novel optical response; thus, GO plays a dominating role in changing the optical absorption behavior of the composite.

The energy gaps of the three produced solutions, yielding a value of 5.22 eV for the PVA solution, Figure 3a, which is consistent with [30], 4.95 eV for the PVA-GA solution, Figure 3b, and 4.41 eV for the PVA/GA/GO solution, as shown in Figure 3c. It is clear that the bandgap decreases with the addition of GA and GO in the PVA. The GO is a non-stoichiometric, filled with defects carbon material whose electrical configuration is determined by the arrangement of sp^2 and sp^3 domains rather than a distinct crystalline band structure. The observed reduction in optical band gap following GO integration does not signify typical semiconductor behavior; instead, it demonstrates improved

electronic coupling, defect-state absorption, and π–π* interactions between GO sheets and the polymer matrix. Comparable decreases in the apparent optical band gap following the insertion of graphene oxide into polymer matrices have been reported, attributable to defect-induced localized states and enhanced charge delocalization [31], [32].

An optical absorption study alone is inadequate to confirm direct applicability in optoelectronic devices; additional electrical and device-level research is necessary.

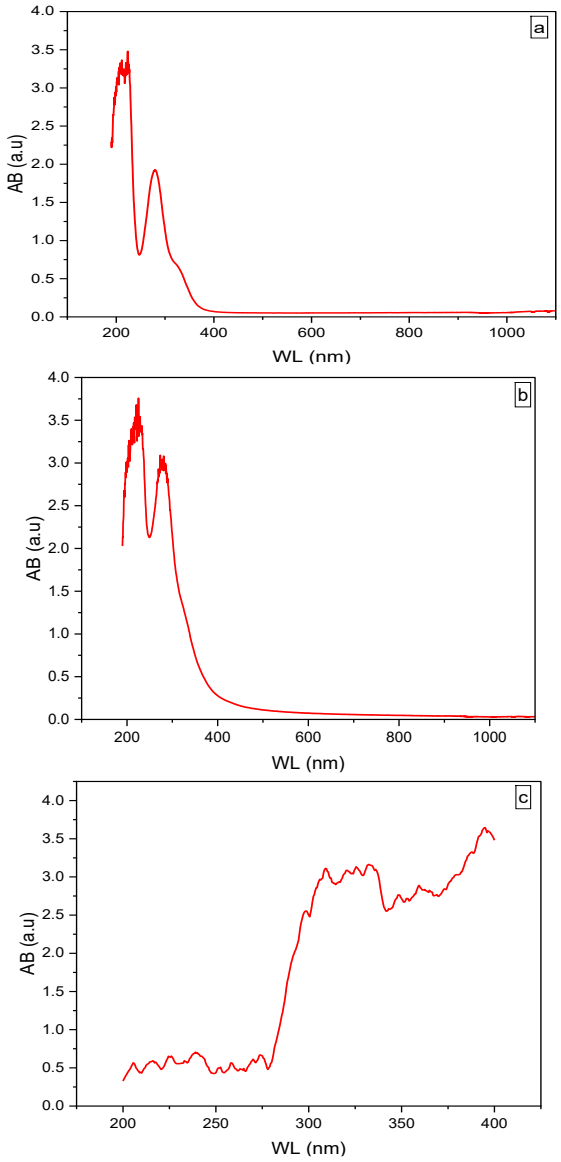


Figure 2: UV-visible spectrum of a) PVA, b) PVA/GA, and c) PVA/GA/GO solutions.

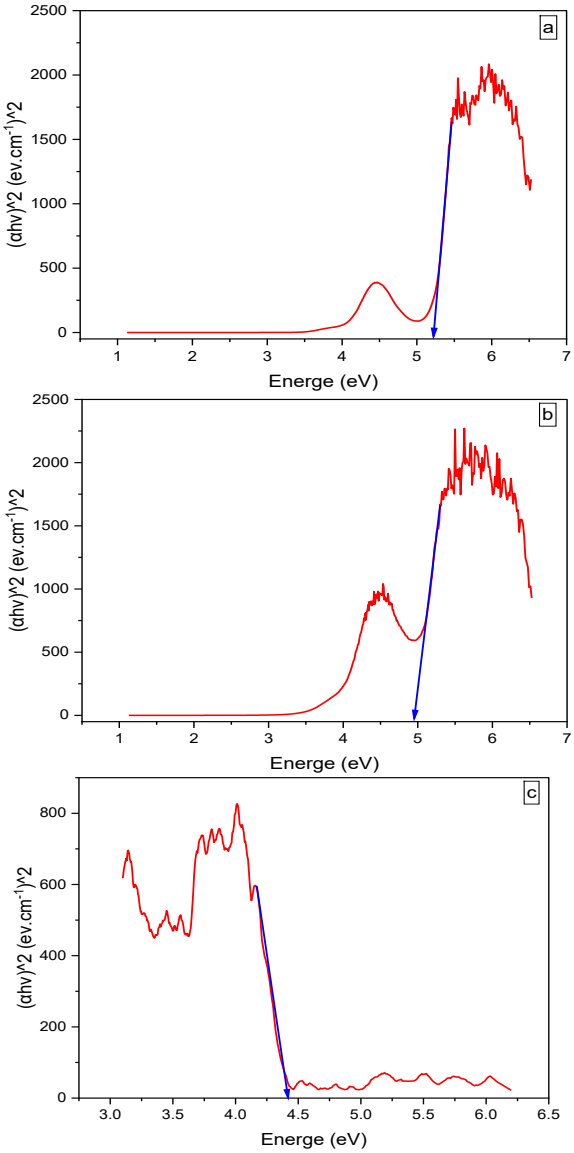


Figure 3: Energy gap of a) PVA, b) PVA/GA, and c) PVA/GA/GO solutions.

3.3 Measurements of Nanofiber Diameters

Although solution viscosity, surface tension, and electrical conductivity were not directly measured in this study, these parameters are well known to have a significant impact on electrospinning behavior. Previous studies have shown that increasing the solution viscosity of the polymer leads to larger fiber diameters [33], [34]. Also, GO is known to reduce fiber diameter by increasing charge density in the jet [35]. Based on recognized electrospinning principles and previously documented patterns in

polymer–polysaccharide and polymer–graphene oxide systems, the observed differences in fiber diameter are therefore qualitatively addressed.

The effect of adding both GA and GO on the formation of PVA nanofibers was studied using a FESEM at 50kx magnification for PVA and PVA/GA and 20kx for PVA/GA/GO. Images were analyzed using ImageJ software to calculate the average diameter of the formed nanofibers, where 50 fibers were measured to determine the diameters. The results showed that the fibers formed from pure PVA were homogeneous and stable, extending to an unlimited length proportional to the amount of solution used, as clearly shown in Figure 4. This result indicates that the base solution is capable of producing continuous, homogeneous fibers under the selected electrospinning conditions.

When 2 wt% GA was added to the solution, 8 wt% of PVA, a significant change in the structure of the resulting fibers was observed, with the fibers appearing discontinuous and irregular, as shown in Figure 5. This change indicates the difficulty of forming cohesive fibers in the presence of GA, which may be due to its effect on the viscosity of the solution or the intermolecular forces during the forming process. GA may have disrupted the flow of the solution during the spinning process, resulting in discontinuous fibers with irregular shape and length.

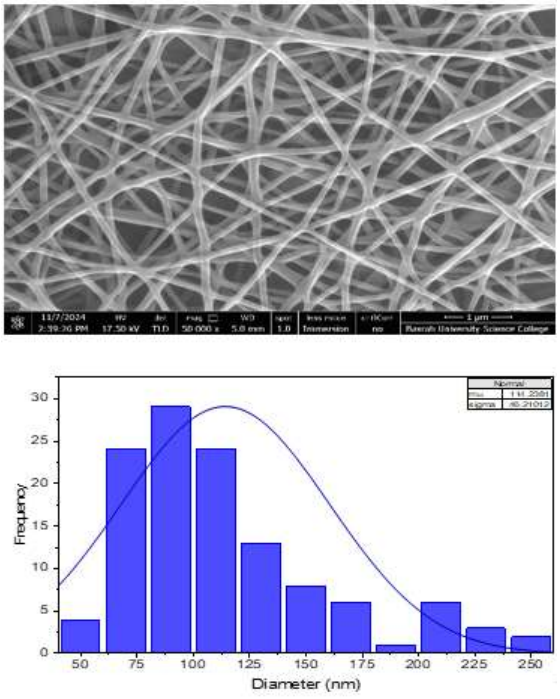


Figure 4: FESEM image of PVA nanofibers and fiber diameter distribution graph using 10 wt% concentration.

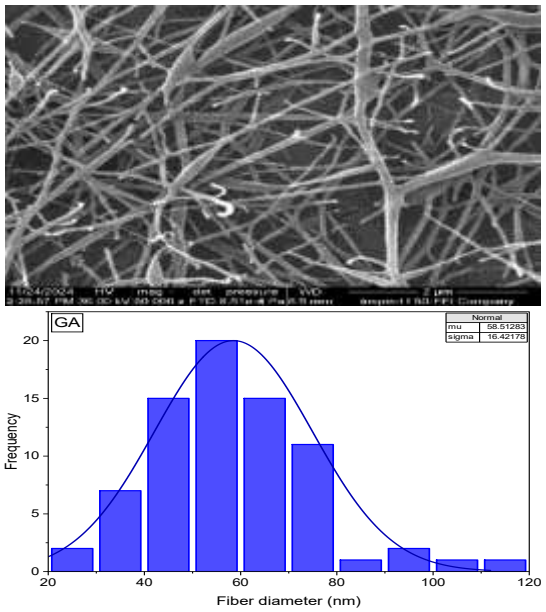


Figure 5: FESEM image of PVA/GA nanofibers and fiber diameter distribution diagram using 2 wt% GA and 8 wt% PVA concentrations.

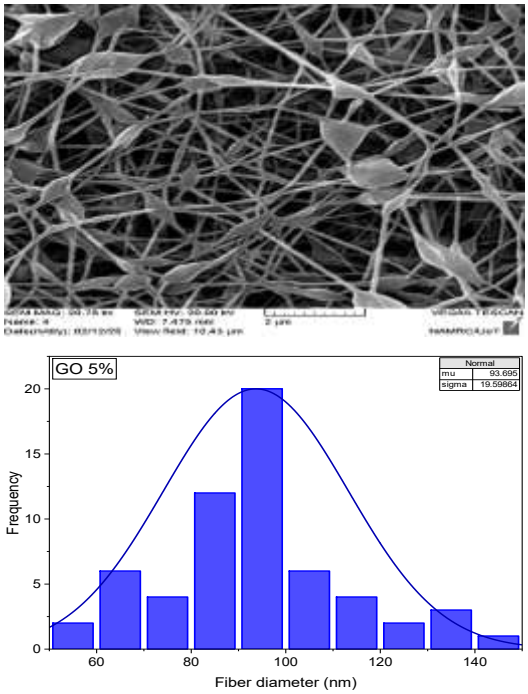


Figure 6: FESEM image of PVA/GA/GO nanofibers and fiber diameter distribution diagram using 2 wt% GA, 8 wt% PVA, and 0.5 wt% GO concentrations.

In an attempt to improve the fiber structure and restore its cohesion, 0.5 wt% GO was mixed with a

solution containing PVA 8 wt% and GA 2 wt%. The results showed that the resulting fibers became more interconnected and continuous, indicating that GO contributed to improving fiber continuity and structural integrity, as shown in Figure 6. This positive effect is attributed to the unique physical and chemical properties of graphene oxide, which likely enhanced the interaction between the various components of the solution, resulting in a more stable and interconnected fiber network.

The creation of continuous electrospun fibers is determined by the balance of solution rheological characteristics and electrical forces acting on the charged jet. The addition of GA, a highly branched polysaccharide, can disrupt polymer chain entanglement and modify solution viscoelasticity, resulting in jet instability and fiber discontinuity. In contrast, adding GO creates conductive channels and raises charge density within the electrospinning jet [35]. This improved electrical conductivity enhances the stretching forces beneath the applied electric field, stabilizing the jet. In addition, GO nanosheets may operate as physical bridges between polymer chains, partially compensating for GA's destabilizing effect and restoring fiber continuity. The seen morphological change can thus be attributed to a combination of GA-induced rheological modification and GO-induced electrical and reinforcing effects.

The mean fiber diameter achieved using pure PVA was found to be 114.23 nm. The incorporation of GA into PVA resulted in a reduction of the average diameters to 58.51 nm. The incorporation of GO into the GA and PVA combination resulted in an increase in average diameters to 93.69 nm.

4 CONCLUSIONS

PVA alone demonstrates minimal absorption in the visible spectrum, with its absorption confined to the ultraviolet range. The incorporation of GA into PVA resulted in a minor alteration of the absorption spectrum, as indicated by the decrease in the energy gap. Adding GO to the mixture significantly improved the absorbance in the visible spectrum, making it the material responsible for the optical modification. The change in optical absorption induced by GO incorporation indicates that the presence of GO would affect the electronic structure of the polymer, which may be of interest for optically sensitive polymer composites.

FESEM results reveal that the incorporation of GA influences fiber continuity and diminishes their diameter, whereas GO enhances the fiber structure's cohesiveness and integrity, increasing the diameter in comparison to GA. This illustrates the possibility of regulating fiber structure and altering its characteristics to suit the needs of specific applications, particularly in applications where controlled fiber morphology is required. Viscosity, surface tension, and electrical conductivity were not measured in this study but will be examined in future studies. Moreover, chemical structure, thermal stability, and mechanical properties need to be considered in future work.

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Remote Sensing-Based Numerical Methods for Water Surface Area Estimation

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Abstract Monitoring water bodies in Iraq is vital in light of increasing climatic and human pressures, especially for Lake Hamrin, a major source of drinking and irrigation water in Diyala Governorate. This research relied on Sentinel-2 L2A images from the Copernicus program for the period 2019–2025 to determine changes in the lake's surface area. The Normalized Water Index (NDWI) was used to extract the water boundaries, then convert the geographic coordinates to metric (UTM) coordinates to accurately draw the shoreline. Two numerical methods were applied to calculate the water surface area of Lake Hamrin the Shoelace and Simpson's methods. Comparing the results with reference values extracted from the Copernicus platform, it was found that the shoelace method yielded a lower error (0.7–3.1%) than the Simpson method (1.3–5.1%). This is attributed to the complexity of the coastal shape of Lake Hamrin. Shoelaces provide a more accurate representation of coastal details, while Simpson's method tends to simplify the boundaries. However, the differences between the two methods diminish when the water level is low, as in 2021–2023, as the shape of the lake becomes more regular.

1 INTRODUCTION

Iraq's natural and artificial lakes such as Tharthar, Habbaniyah, Razzaza, Hamrin, Dukan, Darbandikhan, and the Mosul Dam reservoir are vital pillars of water security, the environment, and the economy (flow storage and regulation, irrigation, hydropower, fishing, and biodiversity) [1]. Over the past two decades, strong observational evidence has accumulated that these bodies of water are subject to increasing pressures due to climate change (increasing temperatures, increased evaporation, and more frequent droughts) and human factors (upstream regulations and transboundary hydropower projects) [2]. This pressure has resulted in shrinking surface area, fluctuating water levels, and deteriorating water quality characteristics. Analyses of water budgets and climate in the Tigris and Euphrates basins show that droughts and extreme heat waves have become a central player in resource scarcity and fluctuating surface storage, with wide-ranging social and environmental impacts [3]. One of the most important of these lakes is Lake Hamrin. It is water basin that was completely submerged in 1981 with the construction of the Hamrin Dam as part of preventative measures against the flooding that plagued Iraqi cities. The lake supplies Diyala Governorate with approximately 70-80 percent of its drinking and agricultural water needs, according to the governorate's Water Resources Directorate, with a capacity of more than 2.4 billion cubic meters of water. Therefore, due to the importance of this lake and other lakes in Iraq, we need to monitor this lake with modern technologies that save time and effort and provide sufficient information upon which to base decisions, especially since the world is experiencing dangerous climate changes. One of the most important of these modern technological methods is remote sensing and the technologies associated with it [4]. At the spatial level, remote sensing imagery has provided a highly reliable time series for tracking water surface fluctuations across Iraq's large water bodies. Recent studies have observed clear seasonal and interannual shrinkage in major lakes such as Tharthar, Habbaniyah, and Hamrin, linking this to increasing climate stress and declining water releases, highlighting the sensitivity of these reservoirs to air temperature and increased evaporation. Other studies have documented the shrinkage of water surface boundaries [4], [5].

In dry and semi-dry environments such as Iraq, peer-reviewed studies have demonstrated significant

shrinkages in major reservoirs and lakes (such as Razzaza and Hamrin) based on Sentinel-2, classification algorithms, and hydrological indices, supporting water management decisions under drought and heat stress. Jumaah et al. (2023) studied the decline of Lake Hamrin using Sentinel-2 satellite imagery and GIS analysis. Using the Normalized Water Index (NDWI), the researchers documented a sharp decline in the lake's surface area between 2017 and 2022, with the water cover decreasing from approximately 144 km² to less than 40 km² [6]. Ameen et al. (2025) extended this research by analyzing the hydrological dynamics of Lake Hamrin over two decades (2004–2024). Using a multi-temporal approach using GIS, they were able to measure spatial and temporal changes in both coastal morphology and water area [7]. Mousa (2022) focused on Lake Sawa in southern Iraq, presenting a comparative case study of the long-term degradation of closed lakes. Using Landsat imagery from 1985 to 2020, the study revealed a continuous decrease in surface area, attributing this to declining groundwater recharge, over-abstraction, and prolonged droughts [8].

Remote sensing is a quantitative framework for non-contact Earth surface observation. Change detection methods were established early on through systematic reviews that formed multi-temporal comparison and their spectral/statistical processing. Capacities have evolved from comparing two or more snapshots to continuous time series observations using all Landsat views. Within aquatic systems, the NDWI and MNDWI spectral indices have become the standard for extracting water bodies and tracking their expansion and contraction in different environments [9].

Sentinel-2 is a wide-band multispectral imaging mission for land and vegetation monitoring, built on a constellation of identical satellites to achieve high pass frequency. Each platform carries a 13-band MSI with 10/20/60 m spatial resolution, a 290 km path width, and a 5-day revisit time at the equator (with two satellites in operation). The S2A (2015) and S2B (2017) satellites were launched, followed by S2C (5 September 2024) to enhance operational continuity. Sentinel-2 is a part of the Copernicus program. Copernicus is the Earth observation component of the European Union Space Program, managed by the European Commission in partnership with the European Space Agency (ESA) and other European stakeholders. It provides data and operational services to support environmental management, climate change adaptation, and civil security, under a policy of free and open access to users. The program includes the Sentinel families (radar, optical, oceanographic, etc.), as well as thematic services (land, air, oceans, climate, emergencies, and security) [10].

2 MATERIAL AND METHOD

The Hamrin Dam Lake (Lake Hamrin) was designated as the research area on the Diyala River, about 120 km northeast of Baghdad, Iraq, 340-square-kilometer. It is an artificial reservoir located between 34° 00′ 30″ to 34° 21′ 30″ N and 44° 52′ 00″ to 45° 12′ 00″ E, created after the establishment of Hamrin Dam in June 1981 Figure 1. The principal objective of Hamrin Dam's construction was to regulate the yearly flooding of the Diyala River; it furthermore functions as a vital irrigation supply and generates electrical power for Diyala Governorate.

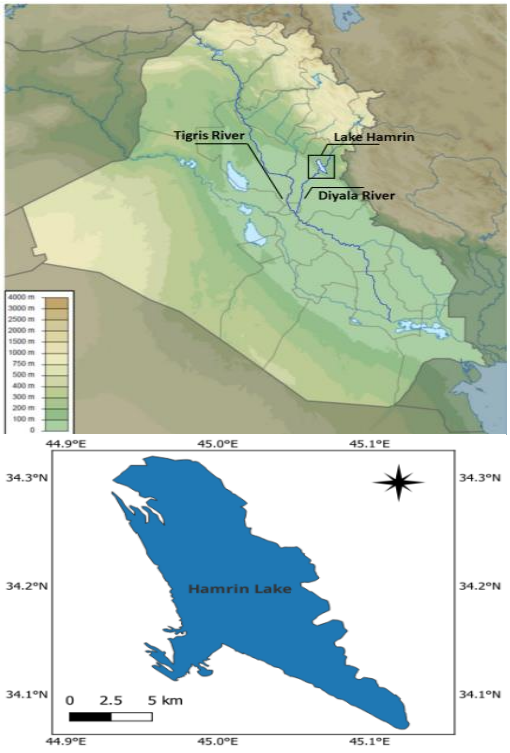


Figure 1: Geographical location of Lake Hamrin within the map of Iraq [6].

Most methods for calculating lake area from satellite images rely on spectral separation of image classes. Then the surface area of water in that lake is calculated using several different mathematical methods. This study introduced numerical method to

estimate the water surface area of the lake Hamrin by Shoelace method and Simpson's. The results of these methods were compared with the calculation of the surface area of the lake water calculated by the Copernicus website [7], [9]. The main steps of this work are explained as Figure 2.

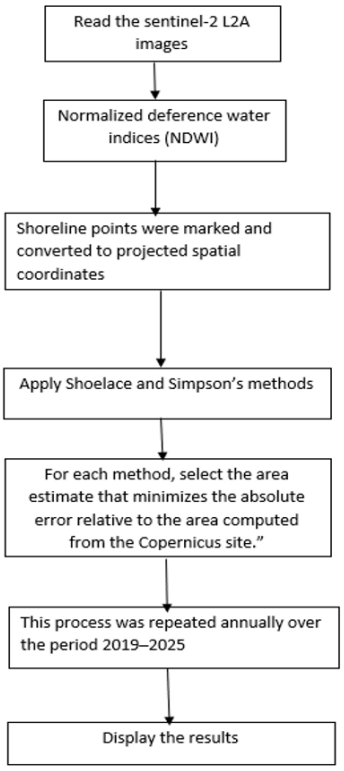


Figure 2: Block diagram for methodology of the work.

The Shoelace algorithm is the standard method for calculating the area of any polygon whose vertices are known in order (the boundary of the lake after being converted to a polygon). It works directly on plane coordinates. We arrange the boundary points x_i, y_i around the circumference (clockwise/ counterclockwise), then add the two "directions" and take half the absolute difference between them [11]. This gives a signed area: positive when arranged counterclockwise and negative when arranged clockwise. For a simple polygon has n vertices the formula of shoelace is given as follow (1):

$$A = 1/2 \sum_{i=1}^{n} |x_i * y_{i+1} + x_{i+1} * y_i|. \quad (1)$$

A is area of polygon.

Simpson's Rule is used to approximate definite integrals and relies on approximating the function using a parabola (a second-degree polynomial) between the division points. The interval is divided into an even number of subintervals [12]. Simpson's Rule is yet another method of numerical integration, given by the (2):

$$\mathrm{J} = \int_a^b f(x) = \frac{\mathrm{h}}{3} [\mathrm{fo} + \mathrm{fn} + 4 \sum_{i=odd}^{n-1} f(i) + 2 \sum_{i=even}^{n-2} f(i)]. \quad (2)$$

Where: $h = \frac{b-a}{n}$.

Sentinel-2 is a European mission that utilizes wide-swath, high-resolution, multi-spectral imaging. Dedicated to Europe's Copernicus program, the mission supports operational applications primarily for land services, including the monitoring of vegetation, soil and water cover, as well as the observation of inland waterways and coastal areas. The twin satellites S-2B and S-2C fly in the same orbit but are phased at 180°, and the full mission specification is designed to provide a high revisit frequency of 5 days at the Equator. In addition, satellite S-2A is temporarily operating at position 36° away from S-2B. Sentinel-2 L2A refers to the Level-2A data processing for the Sentinel-2 satellite, which is part of the Copernicus program by the European Space Agency (ESA).

Sentinel-2 L2A images from the European Copernicus site were used to study the deterioration occurring in Lake Hamrin for a period from 2019 to 2025, where seven images were obtained to cover this period over five years [10], [13]. Locations on the Earth's surface are typically recorded using geographic coordinates, represented by longitude and latitude in degrees. However, this system is impractical when it comes to linear measurements or calculating distances and areas, as it relies on an irregular elliptical surface. To overcome this, geographic coordinates are converted to a projected coordinate system, such as UTM (Universal Transverse Mercator) or Gaussian–Krüger. These coordinates are then converted to metric values (Easing, Northing) on a flat surface. The conversion process is performed using mathematical projection equations that take into account the Earth's elliptical shape. Points are then projected onto a two-dimensional plane using parameters such as the polar radius, central longitude, and scale factor. For example, in the UTM system, the globe is divided into longitudinal zones of 6 degrees width, and the Transverse Mercator projection is applied to each zone to minimize distortions. The result is a metric coordinate system that allows for the calculation of distances and angles with high accuracy, making it essential for applications in geographic information systems (GIS), remote sensing, and surveying. For this purpose, often use GIS tools such as ArcGIS or QGIS [14], [7].

The Normalized Difference Water Index (NDWI) is one of the most important spectral indices derived from satellite imagery. It is widely used to detect surface water bodies (such as rivers, lakes, and reservoirs) and monitor changes in their spatial and temporal distribution. NDWI relies on the spectral contrast between the high reflectivity of water in the green band and its low reflectivity in the near-infrared band (NIR) [15]. The mathematical equation for calculating NDWI is:

$$NDWI = (Green - NIR) / (Green + NIR). \quad (3)$$

Green: Green band reflectivity (usually Landsat band 2 or 3, depending on the sensor).

NIR. Near-infrared band reflectivity (usually Landsat band 4 or 5).

The Sentinel-2 L2A (Level-2A) data from the Copernicus program provide surface reflectance after atmospheric correction, making it suitable for accurate spectral analyses such as extracting water cover indices. The Normalized Difference Water Index (NDWI) from Sentinel-2 L2A is calculated using two channels [16]:

$$NDVI = (B3 - B8)/(B3 + B8). \quad (4)$$

- B3 (Green, 560 nm, 10 m spatial resolution);
- B8 (NIR, 842 nm, 10 m spatial resolution).

We will choose large number of points around the lake shore so that they cover all the details of the shore of lake, including dents, cracks, and bends, so that we get as close as possible from the actual area of the lake's water surface also for more accurate.

A sufficient number of points was selected to cover all details of the lake shoreline, including indentations, curvatures, and irregularities, in order to apply both Simpson's Rule and the Shoelace Formula. This approach ensures achieving high accuracy in calculating the lake's surface area using these methods. Figure 2 illustrates steps the methodology of the work.

3 RESULTS AND DISCUTIONS

The Hamrin Lake is an artificial reservoir created in 1981 after the construction of the Hamrin Dam on the Diyala River in Diyala Governorate, northeastern Iraq. Its variable surface area is approximately 300–400 km², depending on the water storage level. Figure 3 shows two sets of images taken from the Copernicus site during the period from 2019-2025 in the month of July, which represents the drought month in Iraq. A sufficient number of points were marked around the coast of Lake Hamrin, shown in white. After that, the coordinates of these points were recorded and converted from the Geographic Coordinates to the metric coordinates (UTM). The shoelace method and the Simpson method were applied, and the results were included in Table 1.

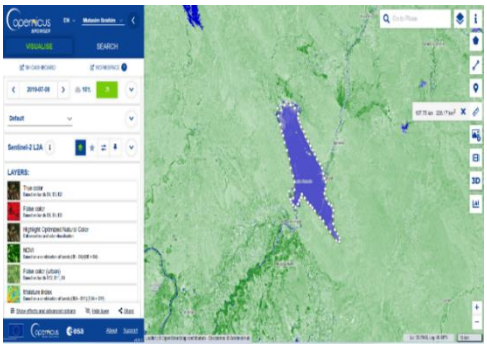
Table 1: The calculated area of water surface of Lake Hamrin in Km^2 using three methods for the period from 2019 – 2025.

Year	Copernicus	Shoelace Method	Simpson's method
2019	107.75	105.2	102.3
2020	77.17	76.11	75.21
2021	38.81	37.61	37.32
2022	36.39	36.13	35.84
2023	49.58	49.12	48.93
2024	81.71	80.51	79.73
2025	101.38	99.34	98.71

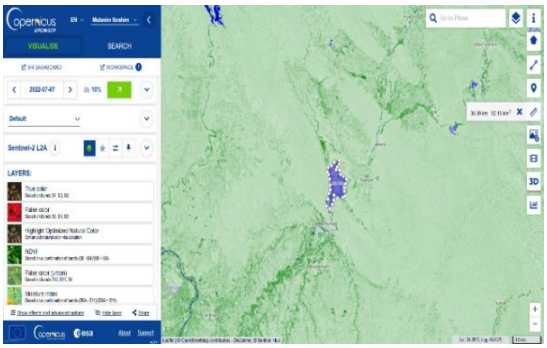
In Table 1, the relative error is defined as the ratio of the absolute error to the reference (true) value. The Percentage Relative Error (PRE) is expressed as follows:

$$PRE = (|Numerical\ Value - Copernicus\ Value|)/(Copernicus\ Value) * 100\% \quad (5)$$

Here, the numerical value denotes the surface area calculated by each method. By applying (5) [17], [18], the percentage relative error (PRE) was obtained for both methods over the study period 2019–2025, thereby providing a quantitative assessment of their accuracy relative to the Copernicus-derived values. The comparison between Copernicus-derived water surface areas and the results of the Shoelace and Simpson's methods demonstrates consistent accuracy across the study period (Fig. 3). The Shoelace method produced values with lower absolute and relative errors (0.7–3.1%) compared to Simpson's method (1.3–5.1%) (Fig. 4). This outcome is logically consistent with the complex geometry of Lake Hamrin's shoreline, which is characterized by numerous indentations and irregularities. Since the Shoelace formula directly utilizes the spatial coordinates of all vertices along the lake boundary, it is able to capture fine shoreline details more accurately than Simpson's numerical approximation. Therefore, the Shoelace method is considered more reliable for estimating the water surface area of Lake Hamrin.



Lake Hamrin 2019



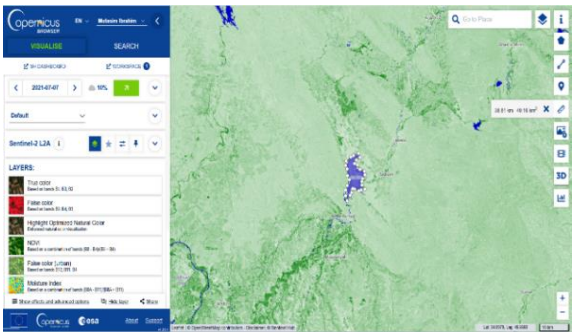
Lake Hamrin 2022



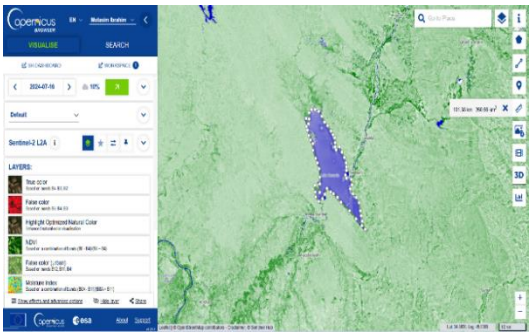
Lake Hamrin 2020



Lake Hamrin 2023



Lake Hamrin 2021



Lake Hamrin 2024

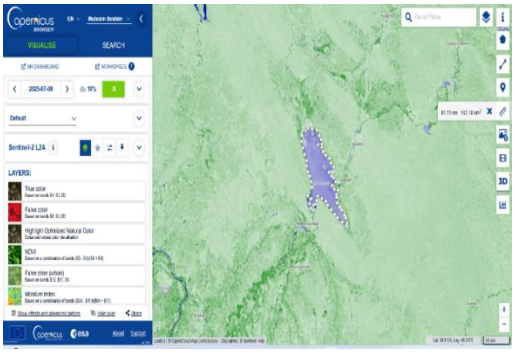


Figure 3: Shoreline of Lake Hamrin marked with white points during 2019–2025.

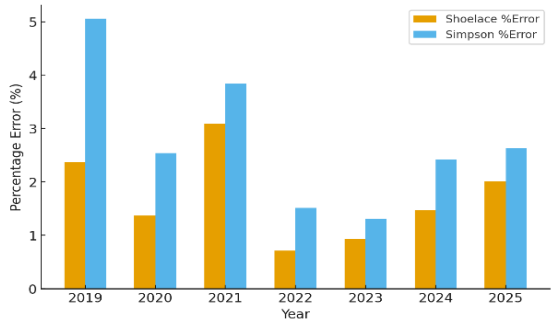


Figure 4: Percentage relative error of shoelace verses simpson's methods (2019–2025).

It can be observed from the Table 1 that during the years 2021, 2022, and 2023 the difference between Simpson's and the Shoelace methods is relatively small. This reduction in discrepancy is primarily attributed to the significant decline in the water surface area of the lake during these years. When the water extent decreases, the shoreline becomes less complex with fewer indentations and irregularities, which reduces the geometric sensitivity of the applied methods. Consequently, both Simpson's numerical integration and the Shoelace polygon-based calculation produce closely aligned results under such conditions. Simpson's method relies on the numerical integration method by dividing the shape into parabolic segments. It is suitable for relatively regular shapes or when the region's boundaries are close to smooth curves. The Shoelace method is a straightforward algebraic formula for calculating the area of a polygon from its vertices' coordinates (x, y). It gives more accurate results for complex and irregular shapes. It relies solely on point coordinates and can accurately represent coastal details if the number of points is large. It does not require integration or approximation assumptions.

4 CONCLUTIONS

The shoreline of Lake Hamrin is characterized by numerous curvatures, indentations, and irregularities, as clearly observed in the delineated boundary derived from Sentinel-2 L2A imagery. Under such complex geometrical conditions, the Shoelace Formula provides a more accurate estimation of the water surface area compared to Simpson's Rule. This is because the Shoelace method directly utilizes the Cartesian coordinates of all marked vertices along the shoreline, thereby capturing even small-scale variations and irregular shapes. In contrast, Simpson's Rule is based on numerical integration and tends to approximate the boundary as smooth segments, which may underestimate or overestimate the area when applied to irregular coastlines. Consequently, given the dense set of points digitized along the shoreline, the Shoelace method yields higher accuracy and reliability for Lake Hamrin's water surface area estimation. The shoelace method is more reliable when dealing with lakes with complex and winding shorelines. The Simpson method may be sufficient when the water surface is low or in regular shapes. Finally, Lake Hamrin has been affected, like the rest of the lakes in Iraq, by a decrease in its water level as a result of climate change and the lack of water releases into Iraq's rivers by neighboring countries.

5 RECOMMENDATIONS

Cooperation with neighboring countries to increase Iraq's water share. Relying on satellite imagery (Sentinel, Landsat) to regularly monitor changes in the lake's area. Preventing agricultural and urban encroachments on the lake basin.

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Multi-Objective Optimization of Design nZEBs in Uzbekistan

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Abstract: The growth in energy demand from the residential sector in Uzbekistan points to the urgency to adopt nearly zero-energy building (nZEB) strategies that can be tailored to domestic climate and economic conditions. The present building stock, represented by weak thermal performance, results in excessive energy consumption for heating and cooling and excessive CO_2 emissions. To address this, the study examines multi-objective optimization methods for residential building retrofitting via integration of advanced insulation systems and renewable energy technology. The calculation uses heating and cooling degree days (HDD/CDD), which is in compliance with national standards ShNK 2.08.01-24 (Thermal Protection of Buildings) and KMK 2.01.04-18 (Building Climatology), to determine energy loads, taking techno-economic factors into consideration in terms of cost-effectiveness. Simulations were conducted for a typical three-room house, varying insulation thickness (0–50 mm), solar collectors, and photovoltaic panels. Results show that particular annual energy requirements decreased from 53.9 to 34.6 kWh/(m²·yr), and CO_2 emission decreased from 45.44 to 18.84 kg/(m²·yr) with improved insulation. Additionally, payback periods decreased from 8.94 to 8.45 years, confirming economic feasibility. The findings suggest that enhanced retrofitting coupled with solar technologies can greatly reduce operational energy usage and environmental impact, offering a sustainable solution for residential development in Uzbekistan.

1 INTRODUCTION

The demand for energy-efficient buildings in Uzbekistan is both environmentally and sustainably required by the climatic variation requirements of a country. An energy understanding of heating and cooling requirements is paramount to building design to the near-optimal energy use levels in Uzbekistan. Heating and cooling degree days throughout the present study are a tool to be analyzed for climatic conditions throughout the region, building insulation, and density to focus on energy efficiency in dwelling buildings. National and international standards, ShNK 2.08.01-24 and KMK 2.01.04-18, are calibrated within the study to offer accurate estimates of energy needs and information regarding energy efficiency and thermal performance that dwelling buildings in Uzbekistan can be designed to offer.

2 MATERIALS AND METHODS

2.1 Data Description

To compare how external temperature variability influences the cooling and heating energy requirements of buildings, this study employed the tried method of heating and cooling degree days (HDD and CDD) [1], [2].

To compare how external temperature variability influences the cooling and heating energy requirements of buildings, this study employed the tried method of heating and cooling degree days (HDD and CDD) [1], [2].

A degree day is the temperature difference (in °C) between the indoor comfort level and the mean daily outdoor air temperature whenever such a difference is larger than some specified base value. The latter depends on the quality of building insulation and on its thermal properties. As specified in the national standard ShNK 2.08.01-24 for Uzbekistan, the reference temperature of the indoor comfort is 20 °C [3].

Different base thresholds were used for buildings with different standards of insulation. Since this variable is quite different by building type, two heating thresholds—10 °C and 12 °C—were selected following the approach of Christenson et al. (2006) [4]. These thresholds were fixed based on each building's volume-weighted heat loss, as computed in accordance with ShNK 2.08.01-24 [3]. In older, non-retrofitted homes, thresholds of 10–12 °C were appropriate, while in newer buildings, there are lower thresholds. In buildings built after 1995, when national thermal protection standards were adopted, the usual heating base temperature of 10 °C was applied to HDD calculation.

The case study is based on a typical three-room residential building, as shown in Figure 1. The geometric characteristics of the building, including room dimensions and calculated areas and volumes, are presented in Table 1.

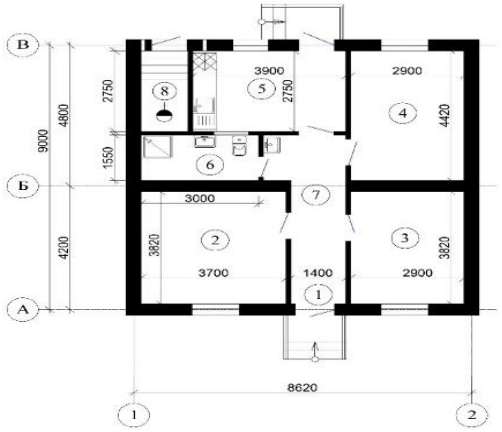


Figure 1: Three-room residential building used as the case study object.

As there is no unified European definition of cooling degree days, most research applies the American standard assuming comfort temperature to be 18.3 °C (65 °F) [5]; [4]. Since this value doesn't include in consideration indoor comfort conditions in Uzbekistan, where by default 20 °C was used, the present research utilized 22 °C as an upper limit of comfort for cooling based on previous works [6]. Accordingly, the indicators of degree-days were calculated as follows:

$HDD = \sum_{i=1}^{n}(20℃ - \theta)$ for n=days per year and $\theta \leq 10℃$, or 12℃,

and cooling degree days (CDD) by

$CDD = \sum_{i=1}^{n}(\theta - 20℃)$ for n=days per year and $\theta \geq 22℃$.

Because residential development across Uzbekistan is spatially heterogeneous, the HDD and CDD values were weighted according to regional population distribution derived from CORINE Land Cover (CLC) data [7]. Thereby, population weighting was applied using Thiessen polygons (for STAR II data) and grid-cell population density (for the CCLM model) to ensure representative climate coverage.

Heating energy demand represents the total heat required to maintain indoor comfort and is affected by transmission and ventilation losses, both of which are temperature and degree-day-dependent. Simultaneously, it is reduced by solar and internal gains, such as heat emitted from electrical appliances and occupants [8]. When outdoor temperatures exceed indoor levels, these heat flows reverse direction, thereby defining the building's cooling energy demand [3].

The annual heating energy demand (Q_h) for each residential building was determined according to the national regulation KMK 2.01.04-18 [9] [10], using:

$$Q_h = 24 \times 10^{-3} \cdot ƒ \cdot HDD \cdot (H_T + H_V) - \eta \cdot (Q_S + Q_I)(kWh/a), \quad (1)$$

where ƒ is the factor for inclusion of a night setback of the heating system temperature=0.95 (kh/d), H_T is the transmission heat losses, H_V is the heat ventilation losses, η is the factor for inclusion of the utilisation factor of internal and solar heat gains, Q_S is the usable solar heat gains (constant value), Q_I is the usable internal heat gains (constant value).

The wall surface specifications and their orientations used in the calculations are summarized in Table 2.

Transmission losses (H_T) quantify conductive and convective heat flow through building elements and depend on the thermal quality (U-values) of envelope components. Lower U-values indicate improved insulation performance [11]. These losses are computed as:

$$H_T = \sum_{i=1}^{4}(F_{xi} \cdot U_i \cdot A_i) + A \cdot \Delta U_{TB}\ (W/K), \quad (2)$$

where F_{xi} is the temperature correction factor (depending on the kind of building component), F_{xi} [wall, window, roof]=1, F_{xi} [basement]=0.6, U_i is the mean U-value of a building component (W/(m^2 K)), A_i is the surface area of each building component (m^2), A is the heat transmitting surrounding area (m^2), ΔU_{TB} is the thermal bridge correction factor=0.05 (W/(m^2 K)).

Ventilation heat losses (H_V) result from air exchange between the interior and exterior. Assuming uniform air tightness for all building types:

$$H_V = 0.19\left(\frac{W}{Km^3}\right) \cdot V(m^3), \quad (3)$$

where V is the heated building volume (constant per building type).

The properties of windows and doors used for solar gain calculations are presented in Table 3.

Solar heat gains (Q_S) arise primarily through glazing and depend on the total solar transmittance (g), window area, and orientation-specific solar radiation intensity (I_i). Assuming full solar exposure:

$$Q_S = \sum_{i=1}^{4} 0.567 \cdot I_i \cdot g_i \cdot A_i \ (kWh/a), \quad (4)$$

where I_i = 155 (East), 270 (South), 55 (West), 100 (North) (kWh/(m^2 a)), g_i is the total energy transmittance of glazing type in case of vertical insolation [–], A_i is the area of windows (m^2).

Internal gains (Q_I) result from occupants and electrical equipment. Due to their variability, KMK 2.01.04-18 [9] recommends the following simplified expression:

$$Q_I = 22 \cdot \left(\frac{kWh}{m^3}\right) \cdot 0.32 \cdot V \ (m^3), \quad (5)$$

For comparability across building types, the simplified KMK approach was also used to estimate annual cooling energy demand (Q_c) [kWh/a]:

$$Q_c = (1 - \eta_{HP}) \cdot (0.024 \cdot CDD \cdot (\sum_{i=1}^{4} F_{xi} \cdot U_i \cdot A_i + 0.05 \cdot A + 0.19 \cdot V) + (\sum_{i=1}^{4} 0.567 \cdot I_i \cdot g_i \cdot A_i + 22 \cdot 0.32 \cdot V)). \quad (6)$$

2.2 Solar collectors

As it intends to cover the energy demand for water heating as much as possible using solar collectors, we introduce two types of solar collectors: glazed flat-plate and evacuated tubular solar collectors. Both types of solar collectors were analyzed for their potential integration into domestic hot water (DHW) installations and combined space heating and DHW configurations (commonly referred to as *combi-systems*). Therefore, we use the annual solar collectors' energy outputs (kWh/year) using the method proposed by the IEA-SHC[1]:

$$Q_{gc_{DHW}} = 0.44 H_0 A_{sc}^{DHW}, \quad (7)$$

$$Q_{gc_{combi}} = 0.33 H_0 A_{sc}^{combi}, \quad (8)$$

where, H_0 is the annual global horizontal solar irradiation (kWh/m^2), A_{sc}^{DHW} and A_{sc}^{combi} are solar collector aperture area (m^2) for DHW system and combi-system, respectively.

Table 1: Room dimensions and calculated areas and volumes.

Name	Width	Length	Height
Hall	1,4	3,82	3
Living room	3,7	3,82	3
Bedroom	2,9	3,82	3
Bedroom	2,9	4,42	3
Kitchen	3,9	2,75	3
W/c	1,55	3	3
Corridor	1,4	5,15	3
Furnace	1,2	2,75	3

Table 2: Wall surface specifications and orientation.

Name	W.r	L(m)	h(m)	Aw (m2)	Ad (m2)	As (m2)
Wall1	West	9,4	3	0	0	28,2
Wall2	South	9	3	3,6	2,5	20,9
Wall3	East	9,4	3	0	0	28,2
Wall4	North	9	3	3,15	4,5	19,35

Table 3: Window and door properties for Solar gain.

Name	W.r	L (m)	Width (m)	Area (Ai)	gi	Ii
Window1	South	1,5	1,2	1,8	0,75	700
Window2	South	1,5	1,2	1,8	0,75	700
Window3	North	1,5	1,2	1,8	0,75	250
Window4	North	1,5	0,9	1,35	0,75	250
Door1	South	2,5	1	2,5		
Door2	North	2,5	0,9	2,25		
Door3	North	2,5	0,9	2,25		

Since the share of air-conditioned dwellings is significantly lower than that of heated ones, the computed cooling demand was multiplied by the proportion of households equipped with cooling units to obtain the actual cooling energy requirement. Equal distribution of air-conditioning systems across building types was assumed.

2.3 Comprehensive Energy Balance Analysis of a Retrofitted Single-Family House

As discussed earlier, the retrofitting measures encompass the addition of thermal insulation to the external walls, ceiling, floor, and roof, along with the installation of a rooftop solar photovoltaic (PV) system and solar thermal collectors to enhance the building's overall energy performance. Therefore, the total annual energy consumption (Q_t^*, kWh/year) in the building after retrofitting can be defined as follows:

$$Q_t^* = \frac{1}{\eta_{wh}}\left[\frac{Q_{heat}^* - Q_{gc_{combi}}}{\eta_{hs}} + Q_{water} - Q_{gc_{DHW}}\right] + E_{el} - E_{PV}, \quad (9)$$

where Q_{heat}^* is the space heating demand (kWh/year) in the building after respective retrofitting envelopes of the building.

2.2.1 Reduction of CO_2-Emission Through the Refurbishment Measures

The emission of carbon dioxide (CO_2) to the environment caused by utilizing energy from the primary energy sources that are obtained by combustion of fossil fuels. The annual CO_2 emission (M_{CO_2}, kg/year) can be defined by the following formula:

$$M_{CO_2} = \mu_f(Q_t - E_{el}) + \mu_{el}\, E_{el}, \quad (10)$$

where μ_f and μ_{el} are the specific CO_2 emission (kg/kWh) due to utilization of fuel (in our case natural gas) and electricity from the local network (obtained by utilizing fossil fuel). Accordingly, after retrofitting, CO_2-emission can be written as follows:

$$M_{CO_2}^* = \mu_f(Q_t^* - E_{el} + E_{PV}) + \mu_{el}\,(E_{el} - E_{PV})\begin{cases} E_{el} - E_{PV} \geq 0 \\ Q_t^* - E_{el} + E_{PV} \geq 0 \end{cases}. \quad (11)$$

2.2.2 The Retrofit Measure

During the simultaneous optimization, retrofitting windows, external wall insulation materials, ceiling, floor, and roof insulation materials and installation of PV panels and solar water heating systems were considered. As items for retrofitting external walls insulation materials, windows, ceiling, floor, and roof insulation materials, the following variables are introduced:

$$U_{win}^* = \frac{U_{win}}{1 + U_{win} x_{ins}^{win}}, \quad (12)$$

$$U_r^* = \frac{U_r k_r}{k_r + U_r x_{ins}^r}, \quad (13)$$

$$U_{ew}^* = \frac{U_{ew} k_w}{k_w + U_{ew} x_{ins}^w}, \quad (14)$$

$$U_f^* = \frac{U_f k_f}{k_f + U_f x_{ins}^f}. \quad (15)$$

which will be used instead of U-values mentioned in (2) for envelopes of the building: x_{ins}^{win} is the R-value of windows; k_r, k_w and k_f are the thermal conductivities (W/m·°C) of insulation materials embedded in the roof-floor external walls, and the floor of the buildings, respectively; x_{ins}^r, x_{ins}^w, and x_{ins}^f are the thicknesses (m) of the same accorded insulation materials.

In the same way, x_{sc}^{DHW}, x_{sc}^{combi}, and x_s^{PV} are variables (m^2) introduced instead of surfaces areas of solar collectors for DHW system and "combi-system", and solar PV panels, which will be designed for the building. Solar collectors and PV panels are installed on the south-oriented roof area. Therefore, it is necessary to optimize solar collectors and PV panels with constrains:

$$x_{sc}^{DHW} + x_{sc}^{combi} + x_s^{PV} \leq \frac{A_r}{2}. \quad (16)$$

2.2.3 Economic Analysis for the Optimal Design

It is obvious that when retrofitting envelopes of buildings and installing solar collectors and PV panels, the initial investment cost of materials increases while reduction of the heating and cooling loads, the electricity consumption from the local network and consequently the energy cost is expected [10]. The optimal design of retrofitting and installation of solar collectors and PV panels is that design, at which the total cost reaches the minima. The total cost is the sum of the cost of all used material and the present value factor (PVF) of the cost of energy consumption over the lifetime of materials that is given by:

$$C_t = (C_{ther} + C_{ae})PVF + C_m, \quad (17)$$

where C_{ther} is the annual energy cost (US $) for supplying the thermal energy is calculated as follows:

$$C_{ther} = \frac{C_{fuel}}{\eta_{hs}}\left[\frac{Q^*_{heat} - Q_{gc_{combi}}}{\eta_{hs}} + Q_{water} - Q_{gc_{DHW}}\right], \quad (18)$$

where C_{fuel} is the specific fuel cost (US \$/kWh). The cost of annual electricity consumption (C_{ae}, US \$) with the specific cost of electricity (C_{el}, US \$/kWh) is:

$$C_{ae} = (E_{el} - E_{PV})C_{el}. \quad (19)$$

The material cost (C_m) is considered as the initial investment cost that consists of:

$$C_m = C_{wall}x_{ins}^{w} + C_{win}x_{ins}^{win} + C_r x_{ins}^{r} + C_f x_{ins}^{f} + C_{DHW}x_{sc}^{DHW} + C_{combi}x_{sc}^{combi} + C_{PV}x_{s}^{PV}, \quad (20)$$

where C_{wall}, C_f, and C_r are the specific costs (US \$/m) of insulation materials for the external walls, floor, and roof, respectively; C_{win} is the specific cost ($\frac{US\,\$}{\frac{W}{m^2 ℃}}$) for windows refurbishment; C_{DHW}, C_{combi}, and C_{PV} are the specific costs (US \$/m^2) of solar collectors for DHW and combi-system, and PV panels.

The PVF depends on the inflation rate g, and the rate of interest i. The PVF can be defined as follows:

$$PVF = \frac{(1+r)^N - 1}{r(1+r^N)}, \begin{cases} r = \frac{i-g}{1+g} & i > g \\ r = \frac{g-i}{1+i} & g > i \end{cases}, \quad (21)$$

$$PVF = \frac{N}{1+i}, i = g, \quad (22)$$

Taking into account time value of investment, the discounted payback periods (in year) of retrofit measure can be defined by:

$$\tau_D = \frac{\ln\left|1 - \frac{rC_m}{C_t - C_{t0}}\right|}{\ln|1+r|}, \quad (23)$$

where C_{t0} is the annual cost of total energy before retrofitting (US \$).

2.3 Optimization Problem and Solution Technique

For simultaneous optimizing envelopes of buildings and integration of various energy generators powered by the renewable energy sources, the optimal designs were considered for three scenarios. As optimization parameters of envelopes, the insulation level of windows, roof, floor, and external walls was considered while as optimization parameters, integrating the solar collectors for the DHW and combined space and water heating, and PV panels on rooftop of buildings were considered. In the first scenario, the life-cycle cost (LCC) is minimized so that the optimal values of parameters are obtained for buildings designed with various levels of thermal insulation. In the second scenario, it is aimed at maximizing the primary energy consumption saving for space heating while minimizing the investment costs. In the final scenario, to create nearly zero carbon communities, the total primary energy consumption is minimized for buildings whereas the investment cost is minimized. The formulated optimization problem was implemented in Python and solved using the package of GEKKO.

Thermal properties and economic parameters of retrofit measure are given in Table 4.

Table 4: Techno-economic parameters of retrofit measure.

Parameter	Unit	Value
Fuel cost	US \$/kWh	0.004
Electricity cost	US \$/kWh	0.029
Insulation cost for roof	US \$/m^3	26.0
Insulation cost for walls		26.0
Insulation cost for floor		26.0
Cost of solar collector (DHW)	USD \$/m^2	300
Cost of solar collector (combi)		200
Cost of solar PV		340
Thermal conductivity of roof insulation	W/mK	0.035
Thermal conductivity of walls insulation		0.04
Thermal conductivity of floor insulation		0.04
Inflation rate	%	17
Interest rate	%	16
Exploitation (lifetime) year	Year	30
DHW demands	kWh/year	3000
Electricity consumption	kWh/year	6000

3 RESULTS AND DISCUSSIONS

The research revealed considerable differences in the Specific Annual Energy Demand as a function of varying levels of insulation. Results (Table 5) show a constant reduction in energy demand from 53.9 kWh/(m²×yr) at baseline to 34.6 kWh/(m²×yr) with an insulation thickness of 50 mm. Initial investment is negatively correlated with the payback period, with a corresponding decrease in payback period from 8.94 to 8.45 years with increased investment. Carbon dioxide emission also decreased significantly with increment in proportionate insulation levels, from 45.44 kg/(yr×m²) at baseline to 18.84 kg/(yr×m²) with 50 mm thickness. The above results emphasize the sustainability of increased building insulation and integration with renewable energy technologies, with PV panels and solar collectors to maximize energy efficiency in residential buildings.

Table 5: Results.

Specific annual energy demand. kWh/(m²×yr.)	Initial investment, mln UZS	Payback periods, yr.	Saved CO2 emission. kg/(yr.×m²)
0	53.9	8.94	45.44
10	50.0	8.87	40.12
20	46.2	8.79	34.80
30	42.3	8.70	29.48
40	38.4	8.59	24.16
50	34.6	8.45	18.84

4 CONCLUSIONS

This study demonstrated that multi-objective optimization integrating building envelope retrofitting with renewable energy systems offers a highly effective pathway toward achieving nearly zero-energy residential buildings in Uzbekistan. Through simulation of a representative three-room house, it was found that increasing insulation thickness from 0 to 50 mm led to a consistent reduction in annual specific energy demand from 53.9 to 34.6 kWh/(m²·yr) and a notable decline in CO_2 emissions from 45.44 to 18.84 kg/(m²·yr). These improvements were accompanied by a modest decrease in the payback period from 8.94 to 8.45 years, indicating that enhanced energy efficiency can be achieved without compromising economic feasibility. The results clearly highlight that insulation improvements, when combined with solar photovoltaic panels and solar thermal collectors, can simultaneously reduce operational costs, energy dependency, and environmental impacts. The integrated optimization approach based on HDD/CDD analysis proved particularly suitable for Uzbekistan's diverse climatic zones, enabling tailored solutions for both cold northern and hot southern regions. Such strategies can serve as a foundation for region-specific nZEB design standards, promoting a balance between cost, comfort, and sustainability. Moreover, the findings underline the importance of adopting national policies and incentive mechanisms that encourage the use of local insulation materials and solar technologies. Scaling up these retrofit and renewable integration measures across Uzbekistan's residential building stock could lead to substantial reductions in national natural gas consumption and greenhouse gas emissions, supporting the country's low-carbon development goals.

Future work should focus on extending this optimization framework to different building typologies (e.g., multi-story or rural dwellings), including dynamic simulations that consider occupant behavior, real-time energy pricing, and lifecycle carbon assessment. Ultimately, the study provides an evidence-based framework for guiding policymakers, engineers, and designers toward a more resilient, energy-efficient, and sustainable housing sector in Uzbekistan.

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Radiation Grafted Copolymerization of Vinylidene Fluoride to Cotton Cellulose and Hydrated Cellulose Fibers

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Abstract: Modifying cellulose hydrate using chemical and physicochemical techniques is one option to get rid of its drawbacks. Radiation-chemical grafting of different monomers is one of the most promising modification techniques [1] for improving the characteristics of hydrated cellulose and its derivatives. Radiation grafting of various monomers to hydrated cellulose (H/c) and its derivatives has been the subject of numerous studies [2], and some of these are now starting to find widespread application in the economy. Given the aforementioned, grafting fluorine-containing monomers onto hydrated cellulose and its derivatives – whose polymers and copolymers have highly valuable and specific properties like chemical resistance, high thermal stability, decay resistance, and hydrophobicity – represents a significant scientific and practical interest [3]. This work aims to synthesise grafted copolymers of hydrated cellulose with vinylidene fluoride from the vapour phase using a radiation-chemical method. The effects of radiation dose intensity, exposure duration, and solvent type on the process and grafted copolymer yield are investigated. Important physicochemical and functional characteristics of the original, irradiated and grafted copolymers are also examined in this study. These characteristics include sorption capacity, density, hydrophobicity, degree of whiteness, mechanical properties, thermal stability, and the type of supramolecular structure alterations brought about by grafting fluorine-containing polymers.

1 INTRODUCTION

Graft copolymerisation with vinylidene fluoride is one efficient method of changing the characteristics of hydrated cellulose fibre textiles. Important physicochemical and functional characteristics of hydrated cellulose, such as sorption capacity, whiteness degree, resistance to microbes, chemical and thermal capacity, and others, are significantly improved as a result. Numerous investigations into the graft copolymerisation process of various vinyl monomers to cellulose have revealed that the yield of the graft copolymer rises when water, alcohols, amines, and dimethyl formamide are present [4]. However, the graft copolymerisation reaction continues with relatively poor efficiency when nonpolar liquids like benzene, toluene, and others are present. Japanese researchers have demonstrated [5] that cellulose swelled in water is adequate for the manufacture of high-yield graft copolymers when cellulose is irradiated with methyl methacrylate, styrene, or another vinyl monomer using γ-rays from Co^{60}.

The objective of this work was to create new copolymers with grafts that combined cotton and hydrated cellulose with a fluorine-based monomer in a lab setting, choose synthesis techniques, and thoroughly examine some physicochemical and operational characteristics of the synthesised samples to identify potential applications.

2 EXPERIMENTAL PART

Cotton cellulose and moistened cellulose fibres served as our first samples. It is noteworthy that the density, molecular packing, and other crucial physicochemical characteristics of these samples vary greatly from one another. The reactivity of cotton and hydrated cellulose fibres is greatly

impacted by a variety of contaminants, including hemicellulose, lipids, wax, lignin, and others. As a result, the samples were completely lubricant-free before being used. We created the monomer vinylidene fluoride (VF_2) by pyrolysing monochlorovanilidene at temperatures between 680 and 700^{0}C; $-CH_2Cl - CHF_2$;

$$CH_2CI\text{-}CHF_2 \quad -HCI \rightarrow \quad CH_2{=}CF_2.$$

Gas chromatography was used to assess the resulting monomer [6] after it had been chemically purified to an exceptionally high level of purity. The presence of two fluorine atoms in the molecule (VF_2) results in the polymer of this monomer exhibiting more pronounced specific properties compared to polyvinyl fluoride. For example, it is more resistant to the action of microorganisms, thermo-oxidative effects, possesses high strength, atmospheric stability, and low water absorption [7]. Therefore, grafting this monomer onto natural fibers represents both theoretical and practical interest. In addition, it should be noted that there is no literature available on the grafting of VF_2 to C/F [8]. Our studies on the radiation polymerization of VF_2 and its grafting onto cellulose fibers showed that it has greater polymerization activity than grafting, compared to vinyl fluoride. Based on this, radiation graft copolymerisation was performed in the presence of vapours of different solvents with an integrated irradiation dosage of 2.5 M rad and a dose rate of 70 rad/sec in order to speed up the grafting rate of C/F and boost the yield of the grafted copolymer.

The obtained results are presented in Table 1.

Table 1: Effect of vapors of various solvents on the grafting degree of vinylidene fluoride onto cotton cellulose.

Solvent	Weight Added %	Content Of PVF_2, %	Solvent	Weight Added %	Content Of PVF_2,, %
Absence Of	0,0	1,2	Isoamyl Alcohol	6,3	7,4
Water	4,1	5,0	Amyl Alcohol	3,1	5,4
Methyl Alcohol	6,7	8,1	Diethylamine	3,1	4,5
Ethyl Alcohol	5,8	7,2	Benchmark: Water 1: 25	5,2	6,8
Propyl Alcohol	4,5	6,6	Acetic Acid	4,1	5,8
Isopropyl Alcohol	6,8	7,1	Dimethylformamide (DMFA)	8,1	11,0

Table 2: Data on the grafting of vinylidene fluoride onto cotton cellulose at different dose rates.

Duration of irradiation	Integral dose of irradiation (M.R.)	Content of PVF_2, %	Inoculation rate % per hour	Radiochemical yield of 10-3 mol/100 eV
Dose rate 11 r/s				
2	0,08	1,5	0,75	5,04
4	0,16	2,1	0,52	3,84
6	0,24	2,9	0,48	3,67
9	0,35	3,4	0,38	2,94
12	0,47	3,7	0,31	2,36
15	0,59	4,2	0,28	2,32
Dose rate 60 r/s				
2	0,43	2,1	1,00	1,45
4	0,86	3,2	0,80	1,12
6	1,30	4,4	0,73	1,03
9	2,04	5,6	0,62	0,86
12	2,59	6,0	0,50	0,66
15	3,24	6,4	0,43	0,63
Dose rate 90 r/s				
2	0,65	2,2	1,10	1,01
4	1,30	4,0	1,02	0,97
6	1,94	5,3	0,90	0,83
8	2,90	5,5	0,61	0,54
11	3,56	7,0	0,63	0,60
15	4,86	8,0	0,53	0,52

Table 3**:** The radiation vapor-phase graft copolymerization of vinylidene fluoride onto H/C was carried out in the presence of vapors of certain solvents with an integral irradiation dose of 2.5 Mrad and a dose rate of 70 rad/sec.

Duration of irradiation	Weight gain%	Content of PVF_2 in copolymer, %	Weight gain%	Content of PVF_2 in copolymer, %
In the vacuum			In the presence of water vapour	
3,0	0,4	0,4	2,0	2,0
5,5	1,0	1,0	2,2	2,1
7,5	1,1	1,1	3,7	3,9
10,0	1,1	2,2	4,4	4,8
13,0	1,6	2,4	5,1	5,3
17,0	1,5	2,3	5,7	6,1
In the presence of methyl alcohol vapors			In the presence of ethyl alcohol vapors	
3,0	2,2	3,2	2,6	2,3
5,5	3,1	5,0	3,0	4,2
8,0	5,4	5,5	3,8	4,5
11,0	6,9	7,08	4,0	4,6
16,0	8,5	8,7	5,1	5,6
17,0	9,0	9,1	6,2	6,6
In the presence of DMFA vapors				
3,0	2,0	2,55		
5,0	3,51	3,52		
8,0	4,8	4,8		
10,0	6,9	7,3		
13,0	10,1	11,5		
17,0	10,3	11,5		

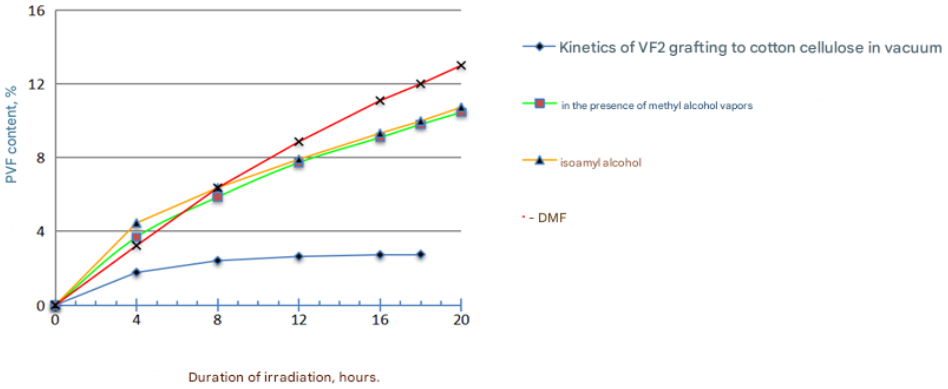


Figure 1: Grafting to cotton fiber.

As seen from Table 1, under the same conditions, the vapors of various solvents have a different effect on the formation of the grafted copolymer. A high graft yield is observed in the presence of a solution of DMF, methyl, isoamyl and ethyl alcohols. Therefore, in studying the kinetic patterns of the graft copolymerization of VF_2 onto C/F in the presence of alcohols, we chose these liquids as solvents. The results of the study on the grafting kinetics are shown in Figure 1, where the graphical dependence of the content of PVDF (poly vinylidene fluoride) in percentage on the irradiation duration is presented. As seen from the data obtained, when grafting was carried out in the presence of solvent vapors, both the grafting yield and the content of poly vinylidene fluoride significantly increased with the irradiation duration.

Under the same conditions, the highest yield of the grafted copolymer is observed in the presence of DMFA vapors. The maximum content of PVDF in the copolymer is 12.8%. In order to study the effect of dose rate on the grafting efficiency, the grafting of VF_2 onto C/F was carried out at dose rates of 11, 60, and 90 rad/sec, within an irradiation time range of 2 to 15 hours, with an initial polymer-to-monomer ratio of 1:2. Table 2.

As seen from the presented Table, at all dose rates, the content of PVDF in the grafted copolymer increases with the irradiation duration. The experiment showed that in the absence of a solvent, VF2 is also difficult to graft onto cotton cellulose; in this case, the grafted copolymer after 19 hours of irradiation at a dose rate of 80 rad/s in the absence of solvent vapors, the yield is 2.2%, and in the presence of methyl alcohol vapors under the same conditions, the yield is 8.1%.

Table 4: Data on the grafting of vinylidene fluoride to cellulose hydrate fiber in the absence and presence of vapors of various solvents (dose rate 70 rad/sec).

Solvent	Weight gain, %	Content of PVF_2 in the copolymer
-	1,0	2,2
Water	3,0	3,5
Methanol	4,1	6,2
Ethanol	2,9	3,2
Propanol	1,8	2,5
Isopropanol	1,9	2,5
Amyl Alcohol	2,8	3,2
Isoamyl Alcohol	2,4	5,3
Diethylamine	3,1	3,4
Dimethylformamide	6,2	7,0

The grafting of vinylidene fluoride to G/c was carried out in the presence of solvents at an integral irradiation dose of 2.5 Mrad and a dose rate of 70 rad/s. The obtained data are presented in Table 3.

As seen from the Table 3, under the same conditions, the vapors of the solvents used have a different effect on the formation of the grafted copolymer. The most favorable effect on the grafting process is exerted by dimethylformamide, isoamyl alcohol, and methyl alcohol vapors. In this case, the yield of the grafted copolymer is significantly higher than in the presence of vapors of other solvents. Next, we studied the kinetics of VF_2 grafting onto H/C in the absence and presence of the vapors of the aforementioned solvents at a dose rate of 70 rad/sec over a wide irradiation time range. The obtained results are presented in Table 4. As seen from the data, grafting of VF2 in the absence of solvent vapors occurs very insignificantly. For example, the maximum content of PVDF after 17 hours of irradiation reached only 2.5%, whereas under the same conditions, in the presence of water vapor, it reached 6.1%, in the presence of methyl alcohol vapors – 9.1%, and in the presence of dimethyl formamide vapors – 11.5%. As a rule, the behavior of the grafting process in the presence of vapors of solvents that cause polymer substrate swelling always leads to an increase in the grafting rate. This pattern was also observed in our case of grafting VF_2 onto hydrated cellulose fabric.

Table 5: Results of grafting vinylidene fluoride onto cellulose hydrate fibers at different dose rates

Irradiation duration, hours	Integral radiation doses, Mr	Content of PVF_2 in the copolymer, %	Inoculation rate, %/hour	Radiochemical yield 10^3 mol/100 eq.
Dose rate 11 r/s				
3	0,12	1,4	0,47	3,42
5	0,20	1,9	0,39	2,81
8	0,32	2,2	0,27	2,00
11	0,44	2,7	0,24	1,83
17	0,73	3,4	0,20	1,27
20	0,89	3,3	0,16	1,20
Dose rate 68 r/s				
3	0,75	3,1	1,03	1,25
5	1,22	5,1	1,01	1,31
8	1,69	5,5	0,68	0,87
11	2,69	7,1	0,64	0,83
13	3,18	8,4	0,64	0,81
17	4,16	9,1	0,53	0,78
Dose rate 100 r/s				
2	0,90	4,2	1,68	1,30
5	1,80	5,7	1,14	0,98
7	2,60	6,4	0,85	0,89
10	3,60	6,3	0,62	0,53
13	4,68	8,5	0,66	0,51
17	6,10	8,9	0,52	0,42
20	7,20	9,1	0,45	0,40

Table 6: The changes in the degree of whiteness of irradiated and grafted H/C fabric samples with VF_2 are shown.

Integral radiation dose, Mr	Degree of whiteness of tissue irradiation%		Grafted copolymers	
	in vacuum	in the vapor of methanol	Content of PVF_2 %	degree of whiteness,%
Initial	79,0			
1,00	78,0	78,0	1,1	79,0
1,67	76,1	79,3	2,8	84,3
2,33	72,2	84,3	3,1	85,0
3,34	70,9	86,0	4,5	91,0
5,01	70,1	83,9	5,2	89,1
6,01	68,5	86,2	9,2	89,1

Table 7: Results of the change in water vapor sorption of grafted copolymers of C/F and H/C with different PVDF content.

Obtained in vacuum			Obtained in the vapour of methanol		
Grafted copolymers of hc fibers					
Starting Materials	0	6,3	0	0,0	6,3
2	0,7	6,0	2	2,6	5,2
4	1,9	5,4	4	4,7	4,4
6	2,1	5,2	9	6,8	4,1
12	2,8	5,0	12	8,0	4,0
15	2,9	4,9	15	9,2	4,3
Grafted Copolymers of G/C Fibers					
Starting Materials	0	11,4	0	0	11,4
3	0,4	10,8	3	3,2	10,0
5	2,0	11,2	5	5,0	10,5
10	2,1	10,8	11	7,0	10,2
13	2,2	10,5	13	8,8	10,0
17	2,3	10,4	17	9,1	9,2

In order to study the effect of different dose rates on the formation of the grafted copolymer, the grafting was carried out in the presence of methyl alcohol vapors at dose rates of 11, 68, and 100 rad/sec, with irradiation doses ranging from 0.12 to 7.20 M/rad (Table 5). From the obtained data, it follows that with an increase in the irradiation duration, at all dose rates, both the grafting yield and the content of PVD_2 in the grafted copolymer increase. The increase in irradiation duration is due not only to the continuous progression of grafting over time but also to the radiation stability of the grafted PVD_2.

As seen from Table 6, as a result of irradiation, with an increase in the integral dose, the H/C fabric significantly loses its whiteness, and the higher the absorbed irradiation dose, the greater the decrease in whiteness degree. When irradiating cotton/linen fabric in a methyl alcohol vapor environment, this effect is only slightly reduced. For example, for the initial H/C fabric, this value is 79%, while for the irradiated fabric at 69.5% Mr, this value increases to 88.9% for the grafted copolymers. For the irradiated fabric in the presence of methyl alcohol vapors under the same conditions, the whiteness degree is 86.2%.

The results of the change in water vapor sorption at 50% relative humidity of grafted copolymers of C/F and H/C with VF_2 are presented in Table 7. From the data provided, it is evident that as the content of PVD_2 increases, the sorption values gradually decrease.

Table 7 presents the results of the study on the mechanical properties of viscose fabrics irradiated in vacuum and in the presence of methyl alcohol vapor, as well as their grafted copolymers obtained under identical conditions. As seen, the properties of the irradiated fabrics, both in the vacuum and in the methyl alcohol vapor environment, are relatively similar. At an integral irradiation dose of 1.62 Mrad, these values remain almost unchanged. As the irradiation dose increases, the tensile strength and elongation decrease slightly. The loss of fabric strength under radiation is also due to the loosening of the cellulose structure [9] and the partial destruction of intermolecular hydrogen bonds [10]. For the grafted copolymer of H/C fabric with PVDF

obtained under the same conditions, the decrease in strength is observed to a lesser extent compared to the fabric modified by the grafting of PVDF. This result is related to the nature of the grafted polymer. It is possible to assume that during the grafting of VF under the continuous action of gamma rays, a large amount of hydrogen fluoride is formed. In this case, an acceleration of the cellulose loosening process is observed, and on the other hand, the higher the content of the grafted polymer, the greater the possibility of the disorienting arrangement of chains in ordered regions, which leads to further weakening of intermolecular bonds.

To study the effect of the dose rate on the changes in the physical-mechanical properties of the fibers, we investigated the changes in the strength and elongation of H/C fibers irradiated in a vacuum and in the presence of methyl alcohol vapor at a dose rate of 90 rad/sec over a wide irradiation time range, as well as their grafted copolymers with PVDF obtained under identical conditions. As seen from the data in Table 8, the strength of the irradiated fibers significantly worsens with an increase in irradiation duration, while the reduction in breaking elongation is less pronounced than the reduction in strength. However, this effect is more noticeable in fibers irradiated in a vacuum. The grafted copolymer obtained under the same conditions loses even more strength.

Table 8: Weight loss of the original, irradiated and modified G/C with PVDF within 12 hours at 230°C, %.

Irradiation duration, hours	Irradiated Samples	Grafted Copolymers	
	Weight Loss	Content of PVF_2, %	Weight loss, %
In the vacuum			
Initial	10,1		10,1
5	10,5	3,3	9,0
10	10,9	4,4	8,2
15	11,2	4,7	8,0
18	11,9	7,2	6,8
		9,0	4,3
In the air			
Initial	27,6	7,2	20,8
18	31,9	9,019,7	
In the vacuum			
Initial	25,1		
22	29,3	7,2	21,7

The obtained results are presented in Table 8. When irradiating H/C in both a vacuum and in the presence of methyl alcohol vapors, its weight loss slightly increases. This effect is explained by destructive processes that lead to the formation of labile points in relation to the effect of elevated temperatures.

3 CONCLUSIONS

Radiation grafting of vinylidene fluoride was performed under various conditions on cotton cellulose, hydrated cellulose, and fabrics based on them in order to improve the most significant physical and chemical qualities and impart new ones. The effects of solvent type and radiation dose rate on the grafting procedure were investigated. The findings demonstrated that the grafting rate and yield increased while decreasing as the dose rate increased. The dosage rate and the grafting rate are proportionate. Due to the hydrophobicity of the modifying polymers, it was found that the sorption and swelling capacities of samples in water increase as the concentration of grafted fluorine-containing polymers increases. Graft copolymers of cellulose and fluorinated polymers have been demonstrated to have improved thermal stability. Additionally, the quantity of weight loss reduces and the decomposition temperature rises with increasing grafted polymer concentration.

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Retrospective Analysis of Student Evaluation of Faculty Using Main Management Information System

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Keywords: Faculty, Retrospective, Main Management System, Student Evaluation.

Abstract: The evaluation of teaching effectiveness through Student Evaluation of Teaching (SET) remains a critical measure in enhancing instructional quality and guiding faculty development. Despite widespread implementation, most studies focus on isolated term analyses, neglecting longitudinal patterns and contextual insights. This study addressed this gap by investigating faculty performance trends from Academic Years 2021–2022 to 2023–2024 using student evaluations stored in the Main Management Information System (MMIS). Specifically, it aimed to determine the level of faculty performance, identify trends and patterns in student evaluations, explore strengths and areas for improvement, and recommend actionable strategies for faculty development. Employing an explanatory sequential design, the study analyzed quantitative data from over 49,000 student evaluations across six domains: learning process, instructional delivery, assessment, learning environment, classroom management, and teacher qualities. This was complemented by thematic analysis of qualitative feedback through text mining. Descriptive and trend analyses revealed an overall "Excellent" faculty performance across all years, with a slight decline in 2022–2023, followed by improvement in 2023–2024. Notably, the learning process and instructional delivery indicators showed fluctuations that mirrored post-pandemic instructional adjustments. Qualitative feedback highlighted strengths such as compassion, clarity, and responsiveness, as well as areas needing improvement, including technological proficiency and emotional sensitivity. These findings suggest that while instructional quality remained high, evolving student needs and rapid shifts in teaching modalities affected performance consistency. The study underscores the value of integrating digital analytics with student narratives to inform evidence-based interventions. It recommends targeted faculty development programs focusing on digital pedagogy, student engagement, and assessment literacy. Ultimately, this study contributes to strengthening institutional capacity for reflective teaching, data-informed decision-making, and sustainable educational excellence in dynamic learning environments.

1 INTRODUCTION

The evaluation of teaching effectiveness remains a cornerstone of quality assurance and faculty development in higher education. Student Evaluation of Teaching (SET) is widely used as both a performance measure and a tool for instructional improvement [1]. Over time, SET has evolved from a summative appraisal to a formative mechanism that promotes reflective teaching. In the post-pandemic academic landscape, where instructional modalities rapidly shifted from remote to hybrid and in-person formats [2], examining the validity and developmental implications of SET data over time has become crucial. However, most institutional analyses remain limited to single-term evaluations, which overlook evolving instructional dynamics and student expectations. Without temporal analysis, SET scores risk being misinterpreted or disconnected from actual teaching transformations [3]. In developing contexts, underutilized digital systems such as the MMIS further limit the potential to harness analytics for faculty development [4].

Globally, institutions are integrating learning analytics to enhance evidence-based teaching evaluations [5], yet the human interpretive element students lived experiences and feedback remains underexplored [6]. This study employed an

explanatory sequential design to analyze MMIS-stored evaluations from 2021 to 2024, identifying statistical trends and exploring their underlying causes. Specifically, it examines faculty performance levels, trends and patterns in evaluations, key strengths and gaps, and strategies to enhance faculty development programs using MMIS data across six instructional domains.

2 METHODS AND METHODOLOGY

This study employed an explanatory sequential and retrospective design to investigate faculty performance based on student evaluations retrieved from the Main Management Information System (MMIS) from Academic Years 2021–2022 to 2023–2024. The quantitative phase involved analyzing student evaluation scores across six key domains: learning process, instructional delivery, assessment, learning environment, classroom management, and teacher qualities as reflected in the instrument. Data were derived from the MMIS answered by the enrolled students from academic years 2021-2024 which varies by number who completed the Student Evaluation for Teachers (SET) instrument in all courses they took handled by the professors during the three academic years, which included three semesters each which include data from different programs such as information technology, computer science, architecture, civil engineering, computer engineering, accountancy, management accounting, business administration, tourism management, hospitality management, physical education, communication, psychology, general education, and senior high school. The instrument utilized was the standardized SET evaluation tool of the university being used both for onsite and online classes. a 7-point scale ranging from "Very Unsatisfactory" to "Truly Exceptional," and ratings were analyzed using descriptive statistics and trend analysis to identify patterns in faculty performance over time.

In the qualitative phase, student narrative feedback from the MMIS was thematically analyzed to identify strengths and areas for improvement in faculty performance. This phase provided contextual insights to supplement the quantitative results and inform relevant faculty development recommendations. Ethical approval was obtained from the university's ethics review board and management. All data were anonymized and aggregated, ensuring compliance with institutional and national data privacy regulations. The limitation of this study was the data which focused only in the SET which excluded the faculty evaluation to students and the data was limited up AY 2024-2025 as SET is administered per Terms, meaning the data from AY 2025-2026 was not yet available.

3 LEVEL OF FACULTY PERFORMANCE BASED ON STUDENT EVALUATION

The evaluation data from A.Y. 2021 to 2024 consistently shows high ratings in the Learning Process component, with overall means ranging from 6.02 to 6.30 (Excellent). Deep and critical thinking scored highest, notably 6.35 in A.Y. 2021–2022 and remained above $\bar{x}$ =6.10 thereafter. A decline in A.Y. 2022–2023, especially in reflection ($\bar{x}$ =6.00), suggests post-pandemic instructional adjustments. Comments such as *"She was able to fully adjust in the finals..."* and *"explains the lessons in a way we're able to understand"* affirm the value of clarity, patience, and scaffolding as summarized in Table 1.

Meanwhile, negative remarks like *"no learning process, no instructional deliveries"* align with lower scores, highlighting inconsistencies. These trends support findings by [7] and [8] that structured communication, collaboration, and reflection shape student perceptions. This underscores the need for continuous faculty training in reflective, student-centered, and flexible pedagogy [9], [10].

Student evaluation data on instructional delivery from A.Y. 2021–2024 showed consistently "Excellent" performance across all indicators, as summarized in Table 2. However, the overall mean slightly declined from 6.28 in 2021–2022 to $\bar{x}$ = 6.00 in 2022–2023, then recovered to $\bar{x}$ = 6.11 in 2023–2024. The dip corresponds with pandemic-related instructional shifts.

Notably, Alignment ($\bar{x}$ = 6.34 → 6.06 → 6.11) and Technology Integration ($\bar{x}$ = 6.33 → 6.01 → 6.11) saw marked decreases in the second year, signaling challenges in maintaining engagement during extended flexible learning. Students remarked, *"Please avoid just reading what was in the presentation,"* and *"All lessons are recorded and students can't even ask questions,"* highlighting reduced interaction and professor presence.

Overall, while instructional standards remained high, real-time engagement and clarity suffered when teaching relied heavily on asynchronous and recorded formats. This aligns with [11], which emphasizes students' need for authentic interaction and timely

feedback in online learning environments. The slight rebound in 2023–2024 suggests adaptation, supported by comments like *"The professor did an excellent job of sparking my interest,"* and *"The professor makes this stressful subject seem like a great intro to programming."*

Table 3 indicates consistently excellent performance across all indicators, with minor fluctuations pointing to areas for improvement. The overall mean declined from 6.26 in A.Y. 2021–2022 to 5.97 in 2022–2023, then rose to 6.10 in 2023–2024, reflecting transitional challenges during the shift to post-pandemic hybrid learning.

Performance-based Assessment remained highest, supported by feedback such as, *"The professors always give us activities to practice communication and teamwork."* In contrast, Feedback showed lower means ($\bar{x}$ = 6.22 → 5.93 → 6.09), with students noting, *"No feedback for students to learn because our papers and quizzes can't get returned in time,"* underscoring the need for more timely and transparent grading.

Qualitative data also pointed to a demand for clearer instructions and assessment transparency. Diagnostic Assessment maintained strong ratings ($\bar{x}$ = 6.28 → 6.01 → 6.10), with students highlighting, "May pre-test and post-test to evaluate learnings." These findings align with [12], [13], emphasizing the value of authentic and diversified assessments.

Meanwhile, declines in enrichment scores and concerns over workload suggest pacing and fairness issues. As [14] notes, effective feedback and fair assessments enhance learner agency, highlighting the need to recalibrate assessment strategies to remain rigorous, transparent, and student-centered, as summarized in Table 4.

Table 1: Distribution of Mean along with Learning Process from 2021-2024.

Indicator	A.Y. 21-22	A.Y. 22-23	A.Y. 23-24	M	Description
	$\bar{x}$	$\bar{x}$	$\bar{x}$		
Deep Thinking	6.35	6.05	6.13	6.18	Excellent
Creativity	6.30	6.03	6.11	6.15	Excellent
Collaboration	6.19	5.95	6.1	6.08	Excellent
Critical Thinking	6.35	6.07	6.11	6.18	Excellent
Communication	6.31	6.03	6.11	6.15	Excellent
Reflection	6.28	6.00	6.11	6.13	Excellent
Overall Mean	6.30	6.02	6.11	6.14	Excellent

n A.Y 2021-2022 = 3010
n A.Y. 2022-2023 = 5201
n A.Y. 2023-2024 = 6926

Table 2: Distribution of Mean along with Instructional Deliveries from 2021-2024.

Indicator	A.Y. 21-22	A.Y. 22-23	A.Y. 23-24	M	Description
	$\bar{x}$	$\bar{x}$	$\bar{x}$		
Learning Outcomes	6.31	6.02	6.12	6.15	Excellent
Alignment	6.34	6.06	6.11	6.17	Excellent
Real-life Connection	6.32	6.03	6.14	6.16	Excellent
Differentiation	6.22	5.96	6.08	6.09	Excellent
Flexibility	6.29	6.02	6.09	6.13	Excellent
Critical Thinking	6.26	5.98	6.12	6.12	Excellent
Learning Resources	6.31	6.02	6.11	6.15	Excellent
Technology Integration	6.33	6.01	6.11	6.15	Excellent
Technology Delivery	6.29	6.02	6.1	6.14	Excellent
Syllabus Adaptation	6.25	5.95	6.1	6.10	Excellent
Simplification	6.27	5.96	6.1	6.11	Excellent
Accessibility	6.22	6.01	6.12	6.12	Excellent
Overall Mean	6.28	6.00	6.11	6.13	Excellent

n A.Y 2021-2022 = 3010
n A.Y. 2022-2023 = 5201
n A.Y. 2023-2024 = 6926

Table 3: Distribution of Mean along with Assessment from 2021-2024.

Indicator	A.Y. 21-22	A.Y. 22-23	A.Y. 23-24	M	Description
	$\bar{x}$	$\bar{x}$	$\bar{x}$		
Integrative Assessment	6.25	6.04	6.12	6.14	Excellent
Real-life Assessment	6.2	5.93	6.12	6.08	Excellent
Diagnostic Assessment	6.28	6.01	6.1	6.13	Excellent
Performance-based Assessment	6.32	6.05	6.1	6.16	Excellent
Flexible Assessment	6.28	5.96	6.09	6.11	Excellent
Enrichment	6.22	5.9	6.1	6.07	Excellent
Feedback	6.22	5.93	6.09	6.08	Excellent
Technology-based Assessment	6.27	5.91	6.1	6.09	Excellent
Overall Mean	6.26	5.97	6.10	6.11	Excellent

n A.Y 2021-2022 = 3010
n A.Y. 2022-2023 = 5201
n A.Y. 2023-2024 = 6926

Table 4: Distribution of Mean along with Learning Environment from 2021-2024.

Indicator	A.Y. 21-22	A.Y. 22-23	A.Y. 23-24	M	Description
	$\bar{x}$	$\bar{x}$	$\bar{x}$		
Cooperative and Supportive Environment	6.31	6.00	6.12	6.14	Excellent
Open Communication	6.30	6.01	6.10	6.14	Excellent
Technology Availability	6.24	6.00	6.11	6.12	Excellent
Interest and Enthusiasm in Learning	6.28	5.96	6.09	6.11	Excellent
Relaxed and Comfortable Environment	6.20	5.92	6.09	6.07	Excellent
Minimized Distractions	6.40	5.92	6.08	6.13	Excellent
Overall Mean	6.29	5.97	6.10	6.12	Excellent

n A.Y 2021-2022 = 3010
n A.Y. 2022-2023 = 5201
n A.Y. 2023-2024 = 6926

The learning environment from A.Y. 2021–2022 to 2023–2024 maintained excellent ratings overall, with a dip in 2022–2023 followed by recovery in 2023–2024. Minimized Distractions scored highest in 2021–2022 ($\bar{x}$ = 6.40) but fell to 5.92 in 2022–2023, indicating difficulties in sustaining focused learning, likely due to digital fatigue and online interaction issues.

Cooperative and Supportive Environment and Open Communication also declined during 2022–2023, reflecting weaker student–teacher dynamics. Students shared, *"Medyo terror po kayo and intimidating"* and *"Always galit tuwing synchronous class,"* contrasting with remarks like *"safe place for us to learn"* and *"interactive approach."* This mix of experiences points to variability in faculty engagement, which affects academic and emotional well-being [15].

Scores improved in 2023–2024, notably in Relaxed and Comfortable Environment and "Interest and Enthusiasm in Learning" ($\bar{x}$ = 6.09), suggesting faculty adaptation and growing use of student-centered pedagogies, aligning with [16], [17], as summarized in Table 5. However, ongoing concerns about unreturned assessments, unclear communication, and classroom atmosphere highlight the need for targeted training in inclusive and empathetic teaching strategies to sustain equitable learning environments.

The results from 2021 to 2024 show a consistent "Excellent" rating in classroom management across all indicators, with a slight dip in the overall mean from 6.23 in A.Y. 2021–2022 to 5.99 in 2022–2023, followed by a modest rise to 6.13 in 2023–2024. Indicators like Class Routines and Session Conduct dropped in the second year, reflecting post-pandemic

adjustments and issues in maintaining regular class schedules, as echoed in student feedback citing irregular meetings and scheduling conflicts. A rebound in 2023–2024 suggests improved structure and delivery, supported by positive student comments. However, lower means in Attention and Engagement and Smooth Activities indicate ongoing challenges with time management and classroom continuity. These findings align with [18], emphasizing the importance of consistency and engagement in classroom management, as summarized in Table 6. Overall, while ratings remain strong, sustained improvement in communication, scheduling, and student interaction remains crucial to maintaining excellence.

A retrospective analysis of faculty evaluations from A.Y. 2021–2022 to 2023–2024 shows consistently excellent ratings across all Teacher Qualities: Subject Knowledge ($\bar{x}$ = 6.22), Communication Skills ($\bar{x}$ = 6.14), Professional Appearance ($\bar{x}$ = 6.23), Positive Attitude ($\bar{x}$ = 6.15), and Technical Skills ($\bar{x}$ = 6.19). A slight improvement in 2023–2024, especially in Subject Knowledge (6.18 → 6.25) and Communication Skills (6.09 → 6.19), suggests gains in teaching competence and relational capacity.

Student feedback supports this trend: *"You always had the patience for my questions and knew just how to explain the answers"* and *"Very nurturing and considerate. She knows what she is doing."* These highlight faculty expertise and student-centered approaches, consistent with literature on engagement and academic success [19], [20].

However, some remarks reveal gaps *"He's a good prof but doesn't communicate well"* and *"She is not techy"* indicating areas for targeted development in communication and digital skills. As [21] notes, professional learning communities and regular feedback loops are essential to address such disparities and sustain pedagogical excellence.

Table 7 shows consistently excellent ratings across six instructional indicators Learning Process, Instructional Deliveries, Assessment, Learning Environment, Classroom Management, and Teacher Qualities with a grand mean of 6.13. The highest scores were in A.Y. 2021–2022, led by Learning Process ($\bar{x}$ = 6.30), Instructional Deliveries ($\bar{x}$ = 6.28), and Learning Environment ($\bar{x}$ = 6.29). A notable dip appeared in 2022–2023, especially in Assessment ($\bar{x}$ = 5.97), likely due to post-pandemic instructional transitions and rising student expectations in hybrid learning.

A modest rebound followed in 2023–2024, particularly in Classroom Management ($\bar{x}$ = 5.99 → 6.13), reflecting improved faculty engagement. Student feedback supports this mix of strengths "He always made sure that everyone of us would learn," "very nurturing and considerate" and areas for growth "Insensitive… nanghihingi pa ng picture ng baha na kasama kami," "She is not techy." These point to the importance of both compassion and technological adaptability.

The fluctuations mirror shifting pedagogical demands and varying faculty readiness, aligning with literature emphasizing ongoing faculty development in digital pedagogy, student well-being, and assessment literacy [22] - [24]. These findings underscore the need for institutional support through targeted training, feedback-driven evaluations, and responsive leadership to sustain instructional quality in evolving learning environments.

Table 5: Distribution of Mean with Classroom Management from 2021-2024.

Indicator	A.Y. 21-22	A.Y. 22-23	A.Y. 23-24	M	Description
	$\bar{x}$	$\bar{x}$	$\bar{x}$		
Class Routines	6.35	6.06	6.16	6.19	Excellent
Session Conduct	6.39	5.98	6.14	6.17	Excellent
Proper Behavior in the Classroom	6.35	6.03	6.15	6.18	Excellent
Learner recognition	6.37	5.98	6.12	6.16	Excellent
Attention and Engagement	6.04	5.97	6.11	6.04	Excellent
Clear Instruction	6.05	5.98	6.11	6.05	Excellent
Smooth Activities	6.03	5.96	6.1	6.03	Excellent
Overall Mean	6.23	5.99	6.13	6.12	Excellent

n A.Y 2021-2022 = 3010
n A.Y. 2022-2023 = 5201
n A.Y. 2023-2024 = 6926

Table 6: Distribution of Mean along with Teacher Qualities from 2021-2024.

Indicator	A.Y. 21-22	A.Y. 22-23	A.Y. 23-24	M	Description
	x̄	x̄	x̄		
Subject Knowledge	6.22	6.18	6.25	6.22	Excellent
Communication Skills	6.14	6.09	6.19	6.14	Excellent
Professional Appearance	6.23	6.19	6.26	6.23	Excellent
Positive Attitude	6.15	6.08	6.21	6.15	Excellent
Technical Skills	6.19	6.15	6.22	6.19	Excellent
Overall Mean	6.22	6.18	6.25	6.22	Excellent

n A.Y 2021-2022 = 3010
n A.Y. 2022-2023 = 5201
n A.Y. 2023-2024 = 6926

Table 7: Summary Distribution of the Teachers' Evaluation from 2021-2024.

Indicator	A.Y. 21-22	A.Y. 22-23	A.Y. 23-24	M	Description
	x̄	x̄	x̄		
Learning Process	6.30e	6.02e	6.11e	6.14	Excellent
Instructional Deliveries	6.28e	6.00e	6.11e	6.13	Excellent
Assessment	6.26e	5.97ee	6.10e	6.11	Excellent
Learning Environment	6.29e	5.97ee	6.10e	6.12	Excellent
Classroom Management	6.23e	5.99ee	6.13e	6.12	Excellent
Teacher Qualities	6.19e	6.14e	6.23e	6.18	Excellent
GRAND MEAN	6.26	6.02	6.13	6.13	Excellent

n A.Y 2021-2022 = 3010
n A.Y. 2022-2023 = 5201
n A.Y. 2023-2024 = 6926

4 TRENDS AND PATTERNS IN STUDENT EVALUATION USING THE MAIN MANAGEMENT INFORMATION SYSTEM

4.1 Learning Process

The learning process evolved from Application-Oriented Deep Learning in 2021–2022 to Fragmented Learning in 2022–2023, and eventually to Instructional Coherence and Learning Continuity in 2023–2024. The initial emphasis on hands-on learning was disrupted by unstructured content delivery, leading to demotivation and shallow engagement, which was later restored by streamlined instruction. This pattern indicates that continuity and coherence are essential to sustain deep learning. Recent studies affirm that a coherent curriculum and active engagement strategies significantly influence student motivation and higher-order thinking [25], [26]. Thus, maintaining structured, application-driven learning is crucial for fostering cognitive development and motivation.

4.2 Instructional Deliveries

Instructional delivery was initially marked by Interactive and Strategic Facilitation in 2021–2022, regressed to Lack of Interactive Pedagogy in 2022–2023, and then improved to Interactive Delivery and Content Accessibility by 2023–2024. The dip in interaction and content variation negatively impacted conceptual understanding, which was later mitigated by reintroducing dynamic tools and teaching methods. This progression indicates that active learning strategies are central to maintaining student attention and comprehension. Research by [16][9] demonstrates that interactivity in both face-to-face and digital settings enhances learner satisfaction and knowledge retention. Consequently, educators must prioritize diverse, student-centered delivery formats to promote engagement.

4.3 Assessment

Assessment practices transitioned from Aligned and Developmental in 2021–2022 to Rigid and Unconstructive in 2022–2023, before improving to Transparent and Formative Evaluation in 2023–2024. The absence of timely feedback and flexibility hindered students' ability to improve during the rigid phase. Recovery was marked by the reintroduction of formative and transparent practices that supported learning autonomy. This reflects the importance of feedback-rich and learner-aligned assessment systems. According to [27], [28], transparent and formative assessment practices promote reflective learning and drive academic success. Institutions should thus embed clear evaluation mechanisms to empower student growth and performance, as summarized in Table 8 and 9.

4.4 Learning Environment

The learning environment shifted from an Inclusive and Psychologically Safe Space (2021–2022), to Disjointed Instructional Design (2022–2023), and rebounded to an Inclusive Supportive Ecosystem (2023–2024). Psychological safety gave way to detachment and low participation when the learning design lacked alignment and support structures. The restoration of inclusive strategies in the final year, such as clearer communication and access to resources, re-established student engagement. This evolution underscores the importance of emotionally and academically supportive environments. Scholars like [29], [30] stress that inclusive learning climates promote belongingness and resilience, especially in times of uncertainty. Hence, inclusive designs should be an ongoing priority in learning environments.

4.5 Classroom Management

Classroom management reflected a progression from Empathetic and Structured (2021–2022), to Ineffective and Insensitive (2022–2023), and back to Structured and Responsive Facilitation (2023–2024). Students initially felt secure with consistent routines, but the loss of structure and emotional awareness disrupted their well-being and focus. By reinstating consistency and empathy in the final year, instructors rebuilt trust and learning efficiency. This variation reveals how crucial adaptive and student-aware

Table 8: Trends and Patterns of Student Evaluations.

Component	A.Y. 21-22	A.Y. 22-23	A.Y. 2023-2024
1. Learning Process	Application-Oriented Deep Learning	Fragmented Learning Undermines Motivation and Cognitive Engagement	Instructional Coherence and Learning Continuity
2. Instructional Deliveries	Interactive and Strategic Facilitation	Lack of Interactive Pedagogy Hinders Clarity and Conceptual Understanding	Interactive Delivery and Content Accessibility
3. Assessment	Aligned and Developmental Evaluation	Rigid and Unconstructive Assessment Limits Student Growth	Transparent and Formative Evaluation
4. Learning Environment	Inclusive and Psychologically Safe Space	Disjointed Instructional Design Reduces Engagement and Inclusivity	Inclusive Supportive Learning Ecosystem
5. Classroom Management	Empathetic and Structured Management	Ineffective Time Management and Insensitivity Affect Student Wellbeing	Structured and Responsive Facilitation
6. Teacher Qualities	Compassionate Professionalism	Teacher Approachability and Competence Drive Student Trust and Learning	Professional Presence and Student-Centered Ethos

Table 9: Strengths and Areas for Improvement in Student Evaluations.

Component	Strengths	Areas for Improvement
Learning Process	Contextualized and Student-Centered Concept Delivery	Inconsistent Instructional Continuity and Cognitive Scaffolding
Instructional Delivery	Engaging, Structured, and Multi-Modal Pedagogy	Disjointed Delivery and Lack of Instructional Depth
Assessment	Fair, Formative, and Supportive Evaluation Practices	Opaque, Misaligned, and Infrequent Feedback Mechanisms
Learning Environment	Supportive, Inclusive, and Application-Oriented Learning Space	Deficient Resource Accessibility and Learning Material Integration
Classroom Management	Structured, Respectful, and Motivational Class Culture	Disorganized Scheduling and Communication Inefficiencies
Teacher Qualities	Empathetic, Passionate, and Professionally Relational Instructors	Inconsistent Presence, Bias Perception, and Emotional Disengagement

management strategies are to academic success. Research by [31] highlights that effective classroom management, grounded in emotional intelligence, directly impacts engagement and behaviour. Therefore, responsive facilitation and structure are essential for maintaining productive classrooms.

4.6 Teacher Qualities

Teacher qualities advanced from Compassionate Professionalism (2021–2022), through Approachability and Competence (2022–2023), to a balanced Professional Presence and Student-Centered Ethos (2023–2024). Students valued empathy and clarity, particularly during challenging periods, but increasingly demanded professionalism and instructional mastery. The final theme reflects a convergence of approachability, fairness, and expertise. This pattern confirms that teacher credibility and interpersonal skills are both vital to effective instruction. According to [32], [33], students respond positively to instructors who exhibit relational competence alongside academic rigor. The implication is that continuous development in both pedagogical knowledge and relational engagement should be central to faculty performance standards.

5 STRENGTHS AND AREAS FOR IMPROVEMENT IN FACULTY PERFORMANCE BASED ON STUDENT FEEDBACK

5.1 Strengths

Student feedback highlights clear strengths in faculty performance, particularly in fostering a student-centered learning process. Many appreciated instructors who made lessons accessible, noting, *"He makes sure that we understand the topic in an easy way,"* and *"Sir explains the lessons in a way where we're able to understand it little by little."* Such feedback shows how contextualized instruction enhances comprehension and engagement [34].

Instructional delivery was also praised for its multi-modal approaches combining videos, live discussions, and demonstrations. Students described methods as *"clear and concise"* and valued explanations offered in *"more than one way,"* affirming that varied teaching strategies improve learning effectiveness [19].

5.2 Areas for Improvement

Despite these strengths, several areas for improvement were identified in the feedback. A recurring issue in the learning process was the inconsistency in instructional continuity, with students noting that *"At first in his subject I had a hard time but eventually I cope with it,"* or *"We wish we had more synchronous classes to truly understand concepts."* This indicates that a lack of regular, live, interactive instruction leaves gaps in students' understanding. Moreover, some students expressed frustration with the instructional delivery being overly reliant on recorded videos or PowerPoint slides. As one student noted, *"He always uses video presentations in lessons rather than teaching only by himself,"* which suggests according to [35] a need for instructors to engage more actively with the students during live sessions, rather than relying too heavily on passive learning methods.

Another notable area for improvement was assessment practices. While some students appreciated the feedback they received, there were significant concerns about the transparency and fairness of grading. For example, feedback such as *"Not transparent about how he calculates our marks" and "Unfair grading, unreasonable pag ggrade nya"* indicate that inconsistencies in grading and a lack of clarity in assessment criteria are major concerns [36]. Students also expressed dissatisfaction with the timing and frequency of feedback, with one stating, *"No feedback for students to learn because our papers and quizzes can't get returned in time."* Such feedback points were noted by [37] to the need for clearer communication regarding assessment expectations, more timely feedback, and better alignment between assessments and learning outcomes. Finally, in the learning environment, students reported feelings of intimidation or discomfort, with some commenting, *"Medyo terror po kayo and intimidating,"* suggesting that while some professors create supportive spaces, others may unintentionally contribute to an environment that hinders open communication and student participation [38].

6 CONCLUSIONS

The longitudinal analysis of student evaluations from A.Y. 2021–2024 across six pedagogical domains revealed consistently excellent faculty performance, with minor fluctuations during the post-pandemic transition. These shifts highlight certain gaps in flexible learning, engagement, and assessment

practices. However, the improvement observed by A.Y. 2023–2024 reflects faculty adaptability and the gradual strengthening of pedagogical approaches.

Overall, the findings indicate that faculty members maintained a high level of instructional effectiveness despite the challenges associated with the transition from pandemic-related learning conditions. Continuous monitoring of teaching performance through structured evaluations provides valuable insights for improving teaching practices and maintaining high educational standards.

7 RECOMMENDATIONS

To sustain instructional excellence, institutions should implement targeted and data-informed faculty development programs focusing on reflective teaching, inclusive communication, responsive assessment, and effective classroom management. Regular evaluations accompanied by actionable feedback can support continuous improvement in teaching practices.

Training initiatives that emphasize emotional intelligence, digital pedagogy, and flexible instructional approaches may further enhance teaching quality and student engagement across different learning modalities.

Future research may focus on longitudinal validation of SET data across institutions, integration of learning analytics within MMIS for predictive insights, and exploration of hybrid evaluation models combining quantitative metrics with qualitative student feedback. Additionally, investigating the impact of faculty development interventions on student learning outcomes would further strengthen evidence-based educational practices.

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Survey of Sensor-Based Arabic Sign Language Datasets

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Keywords: Arabic Sign Language Dataset, Deaf Community, Sign Language (SL), Gesture Recognition, Sensor-Based Recognition.

Abstract: Sign language is the primary means of communication for the deaf and hard-of-hearing community, representing a linguistic bridge that connects them to society and enables them to express their thoughts and feelings. However, Arabic Sign Language (ArSL) still suffers from a distinct lack of scientific research and documented digital databases. This limitation hinders the development of automated recognition systems and weakens their integration into modern artificial intelligence applications. This research aims to review and analyze previous studies related to the use of various databases and sensor technologies in Arabic Sign Language recognition. The study focuses on identifying shortcomings in previous research efforts and proposing methodological approaches to improve data collection and unify standards among researchers. This study relied on an analytical review of scientific literature to extract conclusions and evaluate the effectiveness of previously developed systems in terms of accuracy and efficiency. The results reveal that available databases lack diversity in vocabulary and grammatical structure, which reduces the ability of models to accurately recognize signs. The findings emphasize the importance of developing comprehensive and standardized databases that support the training of intelligent systems, thereby contributing to the integration of deaf individuals into society and improving their educational and social opportunities.

1 INTRODUCTION

Researchers Researchers recognize that the primary mode of communication for those who cannot hear is through sign languages, which rely on movements in all types of human interaction, whether purposeful or incidental [1]. A person who is deaf can truly exercise their rights by learning and using sign languages to receive an education in both sign and spoken language and by helping others understand sign language. To ensure that the deaf community can participate fully in life and learning, it is essential to provide sign language interpretation [2]. According to the World Health Organization, one billion people, or 14% of the world's population, live in Arab nations and utilize the Arabic alphabet [3]. Several Asian and African languages and dialects including Kurdish, Punjabi, Sindhi, Balti, Balochi, Lurish, Urdu, Kashmiri, Somali, and Mandinka, as well as the inhabitants of Arab nations employ Arabic alphabets [4]. Since almost 25% of the global population utilizes Arabic alphabets, their significance is evident.

Despite the growing need for Human-Computer Interaction (HCI) driven by advancements in sensor technology, Arabic Sign Language (ArSL) has not advanced as much as other sign languages such as American Sign Language (ASL), British Sign Language (BSL), Vietnamese, Chinese, and various others. Additionally, little is known about the Middle East's classification and translation of sign language with the goal of using contemporary technological tools to assist those with impairments. Arabic computer programs designed to assist individuals with impairments in their education also possess flaws. Despite the great diversity of sign languages, where each has its own syntax and rules, the only similarity is that they are all visually perceptible [5]. Furthermore, outside of the deaf population, knowledge of sign language is not very common. Many deaf children are born to hearing parents; thus, even within the family, there is a linguistic barrier. Deaf individuals are often taught to be multilingual in reading and writing because there are no established protocols for sign languages [6]. Additionally, there is a vast array of sign languages. The employment of facial expressions, head movements, and hand

gestures to transmit meaning constitutes the linguistic features of sign language [7]. Studies on recognizing hand movements began with gloves equipped with multiple sensors and trackers as part of a sensory method. These gloves provide accurate information about hand position and finger movement, which aids in recognizing Arabic Sign Language [6]. Other initiatives employ different sensor types, such as cameras like the Microsoft kinect [8]. The goal of these systems for recognizing Arabic Sign Language is to create a method to occasionally replace human interpreters by converting sign language shown in videos or images into Arabic text. Additionally, this method aims to encourage better and more inclusive communication by enhancing exchanges between deaf and hearing individuals.

2 CLASSIFICATION OF ARABIC SIGN LANGUAGE RECOGNITION

Creating a structure for recognizing Arabic Sign Language (ArSL) necessitates collecting a substantial dataset of sign language, which must be accurately labeled with the corresponding signs. This collection can be utilized to educate and evaluate models in the classification phase of machine learning. Information regarding the recognition of Arabic Sign Language can be obtained through two approaches [9]: the first is a sensor-based strategy [10], and the second is a vision-based strategy, as seen in Figure 1.

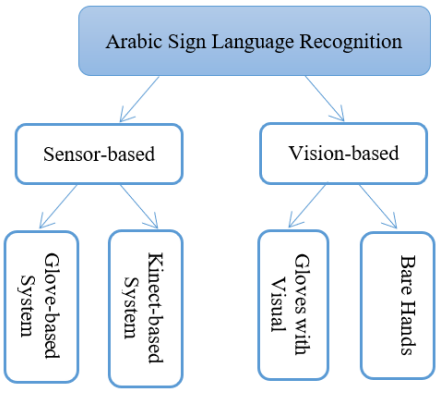


Figure 1: Approaches for recognizing sign language [11].

The method of recognizing Arabic Sign Language through visual means focuses on the analysis and interpretation of sign language gestures captured in images or videos with the help of computer vision methods. The sensor-based method for recognizing Arabic Sign Language employs sensors to identify and record information related to sign language gestures. This technique can be utilized either as an alternative or as a complement to visual methods, presenting several benefits and drawbacks. One benefit of utilizing sensors is their ability to yield more precise and dependable data compared to visual methods, particularly in situations with low lighting or obstruction. Additionally, sensors can capture data that may not be visible to the human eye, including signals from electromyography, as well as measurements of force and pressure. There are two primary types of systems: glove-based systems [12] and Microsoft Human Pose Estimation-based systems [13]. Gloves can be used in systems that read hand gestures (see Fig. 2) because of their mechanical and electrical components [12].

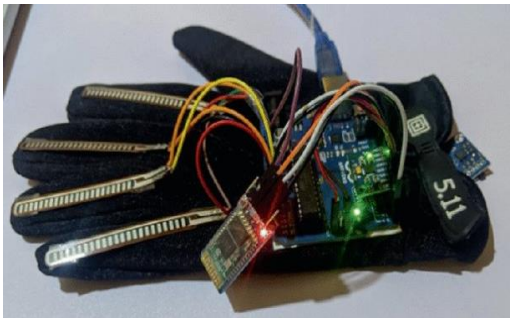


Figure 2: Smart glove with sensors.

Even though this approach can produce beneficial results, using a glove linked to specific sensors (Fig. 3) that capture data may pose difficulties for individuals who rely on sign language and have speaking or auditory impairments [14].



Figure 3: Microsoft human pose estimation sensor.

This can be accomplished through either a vision-centric or a sensor-centric method. A method for identifying the ArSL alphabet involves regarding each letter as a unique gesture and applying machine learning strategies to categorize the gestures

according to visual or sensory characteristics. Typically, a fixed state and a limited vocabulary are employed to convey letters. While the Arabic alphabet consists of merely 28 letters, the Arabic Sign Language contains 39 symbols [15], [16]. Instances of basic symbols that consist of a pair of letters include eleven extra symbols. For instance, these two letters resemble the English word "the" and are exceedingly prevalent in Arabic [17].

Isolated word identification, unlike the recognition of alphabetic symbols, centers on a collection of movements that relate to individual words, each carrying its own meaning and significance. It treats every term in Arabic Sign Language as a distinct gesture and categorizes gestures based on the established system built around them.

On the other hand, the method of continuous sign recognition presents greater challenges when discussing execution. The challenges linked to this approach include tracking hand movements, recognizing motion, identifying features, and handling an extensive vocabulary. Once the appropriate feature vector is acquired, classification is simplified because of the various methods that the system can utilize.

3 ARSL RECOGNITION CHALLENGES

Sign language does not have a standard form. Regional and dialectal differences set Arabic Sign Language apart from spoken languages. The great majority of Arabs can understand Arabic Sign Language, and it is the focus of our interest in this study [18], [19]. Learning the deaf community's language and creating Arabic Sign Language learning models are necessary to improve the Arab community's comprehension and integration of the deaf community. To make it possible for a larger portion of the population to interact with deaf and mute people in an efficient manner, and to partially replace human translators, a system that can interpret sign language should be created. To encourage more inclusive and smooth encounters and enhance communication between the deaf population and others, the complexity and diversity of sign language movements must be addressed. This complexity is one of the biggest obstacles to creating a framework for Arabic Sign Language detection. A variety of hand gestures, body postures, facial emotions, and body movements are all part of sign languages, which are intricate visual languages. The distinct grammar and syntax of Arabic Sign Language, in particular, make it difficult to model and recognize using traditional machine learning methods. To solve these challenges, various techniques for recognizing sign language have been employed by researchers. A significant factor to keep in mind while creating a framework for sign language recognition is the availability of an extensive database that researchers can depend on to advance their research. This is the primary emphasis of the current study [20], as the lack of availability of a data set or the existence of only small sets that do not meet the researcher's needs hinders the development of projects and progress within the framework of Arabic Sign Language recognition. The availability of pre-made data that meets necessary requirements eases the workload and time commitment for researchers, which raises interest in this language as a study subject; consequently, findings, development, and outcomes improve. In contrast to other languages, there are not many databases accessible in Arabic Sign Language, per earlier research.

4 TRAINING DATA SETS

There are a number of ways to capture gestures in sign language; however, studies suggest that the focus on gloves is more comprehensive and broader. People are drawn to the sensory glove because of its capacity to capture the data required to depict the hand's structure and motion in order to identify the motions of the source language. Although there are many positions in the source language, much of the research has focused on a small subset of these positions, which may be as few as several letters of the alphabet [21] - [23]. Additionally, researchers use the most common word positions in the source language [24] - [28], using a mix of words, numbers, and alphabets [29] to carry out their research and create an SLR system. The collection of gestures has been expanded by others with the intention of creating a system that can differentiate between them. Some datasets contain whole alphabets [30] - [33], others utilize numbers between 0 and 9 [34] or include both in the same system [35] - [37]. In addition, other researchers contributed by differentiating between certain words, phrases, and even phrases chosen to depict a range of real-life scenarios, such as family, shopping, school, sports, etc. [38] - [41].

Table 1 provided information on the Arabic Sign Language dataset studies using sensor-based

recognition utilized in the majority of the earlier research. This information includes the kinds of gestures used and how frequently they are used. The Table 1 also shows the number of performers and the creators of the signs. The total number of samples used in the trials is also provided.

5 CONCLUSIONS

This paper has provided an outline of the Arabic Sign Language recognition systems that are currently accessible in the public domain, specifically those that include databases and use sensor approaches to detect Arabic Sign Language gestures. Many aspects related to Arabic Sign Language have been explored and investigated. There is a sign language for almost every country; however, sign language studies have not yet satisfied the needs of each language. Despite the importance of this topic, published scientific research on Arabic Sign Language recognition is limited, especially regarding articles that use sensor approaches. In addition, techniques for recognizing sign language have been reviewed in this work.

Table 1: Arabic sign language dataset using sensor-based recognition.

Author	Language	Components	Gesture	Sample per Gesture	Gesture Performer	Sample Size
[42] 2021	Arabic Sign Language	Six IMUs sensors	28Arabic alphabets	25 samples per gestures.	Seven young volunteers (three male, four female)	4900 samples
[43] 2020	Arabic Sign Language	Two Glove each have 5 flex and (MEMS) module MPU-6050	30 words and 15 expressions	One time	Two users	45 tested
[44] 2021	Arabic Sign Language	Microsoft Kinect V2 Sensor	502 signs	50 times, each signer repeats	Three professional signers	75,300 samples.
[46] 2024	Arabic Sign Language	five flex sensors, MPU6050, An accelerometer gyroscope, MAX30102 sensor.	12 Alphabets, 8 words	One time	One user	20 tested
[47] 2019	Arabic Sign Language	Five flex and one-accelerometer sensors	five Arabic letters	Four times	Four user	80 Samples
[13] 2018	Arabic Sign Language	Kinect Sensor	30 isolated words	40 times	10 different signer (four women and six men).	1200 samples
[48] 2021	Arabic Sign Language, English Sign Language	Five flex and one-accelerometer sensors	29Arabic alphabets 26English alphabets	20 times	One user	580 Samples Of ArSL
[49] 2023	Arabic Sign Language, English Sign Language	Five flex and one-accelerometer sensors	28Arabic alphabets 26English alphabets	200 examples of each letter in both ASL and ArSL. (except J and Z)	One user	5600 Samples Of ArSL
[50] 2014	Arabic Sign Language	Two CyberGloves	(100) two-handed signs.	20 times	An adult deaf community volunteer	2000 samples
[51] 2023	Arabic Sign Language	potentiometer for each finger, MPU6050	40 ArSL words	One time	10 deaf people	400 Samples
[45] 2015	Arabic Sign Language	DG5-VHand data gloves	40 sentences 80-word lexicon	Ten times	Right handed young female	800 samples

The findings show that there are currently three methods in the field of sign language recognition. The first approach is vision-based systems; the second approach, widely used in this field, relies on sensors as the primary source of data capture; and the last approach is a hybrid technique combining the first and second approaches. Many researchers have proposed ways to recognize Arabic Sign Language and have provided reported datasets. However, for testing and evaluating their systems, researchers are unable to access any standard Arabic Sign Language datasets. A number of datasets have been promised for public release. Although they have not yet reached the status of "reference datasets" among Arabic Sign Language recognition researchers, they are considered promising solutions to motivate researchers. There is a need to stimulate efforts toward enhancing digital documentation to facilitate more in-depth research and expand the body of knowledge on Arabic Sign Language. Investment in scientific research is crucial, as is increasing cooperation between academic institutions, organizations for the deaf, and government agencies. Addressing the problem of limited access to data due to intellectual property rights or regulatory restrictions is vital. Furthermore, launching joint research initiatives between Arab countries and academic institutions would contribute to unifying efforts and encouraging institutions to provide Arabic Sign Language databases openly and freely to researchers and developers. All of this will contribute to increasing interest in Arabic Sign Language and its documentation, which enhances communication with the deaf community and contributes to increasing educational opportunities and social integration.

6 FUTURE WORK

There are several future aspirations that will improve the standard and strengthen the scientific foundation of this field. One is the potential for developing a single, all-inclusive database that can be used for research and development, encompassing all dialects in Arab nations while accounting for regional linguistic variety in signs. Advanced technologies, such as those that track hand positions, facial expressions, and body movements, can also be used to improve the database's quality and comprehensiveness. This is in addition to expanding scientific collaboration both worldwide and within the Arab world to promote advancements in this area.

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Innovation-Driven Analysis of Social Project Mechanisms for Renewable Energy Transition

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Keywords: Renewable Energy, Public Perception, Social Acceptance, Stakeholders, Communication, Media Analysis, Social Trust.

Abstract: This study focuses on the public perception and social acceptance of renewable energy projects, as well as on the analysis of mechanisms for stakeholder and community engagement. The article examines the main factors influencing public support for renewable energy initiatives, including levels of awareness, trust in project developers, environmental concerns, and cultural contexts. A comprehensive analysis of survey data, media content, and case studies of both successful and unsuccessful projects was conducted. Based on these data, models were developed to explain the interrelations among key factors, and practical recommendations were formulated to enhance community support for renewable energy initiatives. Particular attention is given to the role of communication, transparency, and community participation at all stages of project implementation. Public perception and social acceptance are interpreted as multidimensional phenomena encompassing psychological, cultural, economic, and political dimensions. Theoretical frameworks applied in this research include the diffusion of innovations theory, social capital model, trust theory, and risk perception models. The analysis demonstrates that active stakeholder involvement and transparent communication substantially increase public trust and support for renewable energy initiatives. Furthermore, the use of advanced methods of social media analytics and network analysis enables the identification of key sources of both negative and positive sentiment, which is essential for designing effective public opinion management strategies. The results confirm the need for a systemic and interdisciplinary approach to accelerate the transition toward sustainable energy systems. The study provides practical recommendations for policymakers, businesses, and research institutions aimed at enhancing social support for renewable energy projects and reducing resistance from local communities.

1 INTRODUCTION

1.1 Relevance and Scientific Significance

In recent decades, the transition to sustainable energy sources has become a central theme in both scientific discourse and practical policymaking related to energy security, greenhouse gas emission reduction, and climate change mitigation [1]. Within the framework of global initiatives such as the Paris Agreement, renewable energy projects-including solar, wind, and hydroelectric systems-have gained strategic importance in achieving the United Nations' Sustainable Development Goals (SDGs) [2].

However, the deployment of renewable energy technologies often encounters a range of social and cultural barriers associated with public perception and social acceptance. The way renewable energy projects are perceived by local communities, stakeholders, and the wider public substantially

influences their successful implementation [3]. Insufficient awareness, fears regarding ecological or social impacts, and region-specific cultural or historical factors can all serve as obstacles to the adoption of new technologies [4].

The scientific community increasingly emphasizes the need for comprehensive approaches to community engagement and stakeholder collaboration in order to enhance support for renewable energy initiatives [5]. Within this context, the concept of social acceptance has evolved, encompassing not only formal approval but also the levels of trust, endorsement, and active participation of citizens in renewable energy projects [6].

1.2 Historical Context and Current State of the Problem

Historically, global energy development has been dominated by centralized fossil-fuel systems based on oil, coal, and natural gas. Since the late twentieth century, however, the need to transition toward cleaner and more sustainable energy sources has become increasingly urgent. Renewable energy projects are now regarded as a strategic necessity for mitigating the environmental consequences of traditional energy technologies [7].

Despite their clear environmental and economic advantages, renewable energy initiatives frequently face resistance from local populations. For example, wind power projects have in some regions triggered opposition due to concerns about landscape aesthetics, noise pollution, and potential ecological risks [8]. Similarly, solar farms are sometimes met with skepticism about their efficiency or possible environmental impacts on local flora and fauna [9].

Contemporary research underscores the importance of integrating social dimensions into the planning and implementation processes of renewable energy projects. In particular, special attention is given to stakeholder participation, transparent communication, and the social responsibility of project developers [10].

1.3 Theoretical Foundations and Key Concepts

Public perception and social acceptance are multidimensional phenomena encompassing psychological, cultural, economic, and political dimensions. The principal theoretical frameworks applied to the analysis of these processes include:

- Diffusion of Innovations Theory (Rogers), which explains how new technologies spread within societies.
- Social Capital Theory, emphasizing the role of social networks and trust in collective decision-making.
- Trust Theory, exploring the relationship between institutional credibility and acceptance of technological change.
- and Risk Perception Models, which account for how individuals and communities assess and respond to perceived technological and environmental risks [11].

These frameworks collectively provide the analytical foundation for understanding the complex mechanisms behind social acceptance and for developing strategies to foster greater public support for renewable energy projects (Table 1).

Table 1: Key factors influencing public perception of Renewable Energy projects.

Factor	Description	Impact on Perception
Information Support	Providing accurate and transparent information to the public about the project	Increases trust and reduces uncertainty or fear
Environmental Risks	Potential negative impacts on the natural environment	May cause public resistance or opposition
Economic Benefits	Creation of jobs and reduction of household or regional energy costs	Encourages public support and engagement
Cultural Context	Consideration of local traditions, community values, and historical heritage	Plays a crucial role in decision-making and acceptance
Trust in Project Developers	Public confidence in the integrity, transparency, and competence of implementing actors	Determines the overall level of social acceptance

1.4 Contemporary Challenges and Prospects for Community Engagement

One of the major challenges in implementing renewable energy projects is the insufficient public awareness, which often leads to misconceptions, concerns, and resistance. In this context, the development of comprehensive public information and education programs, as well as the active participation of stakeholders at all stages of project realization-from planning and design to operation-becomes particularly crucial [12].

Effective community engagement is increasingly recognized as a cornerstone of sustainable energy transitions. Transparent communication, early consultation with local populations, and co-creation of project strategies foster a sense of ownership and shared responsibility. Furthermore, integrating community-based decision-making into project governance helps mitigate conflicts and enhances long-term social acceptance.

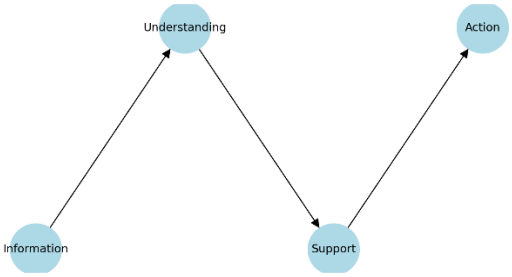


Figure 1: Model of Social Acceptance of Technological Innovations.

Future prospects for improving public engagement involve the use of participatory digital platforms, social media analytics, and deliberative forums that allow for continuous feedback and dialogue between developers, policymakers, and citizens. Such approaches not only strengthen trust but also ensure that renewable energy projects align with local values, environmental priorities, and socio-economic needs.

Figure 1 illustrates the logical sequence of stages in the formation of public acceptance of technological innovations. The process begins with the "Information" stage, where the public gains initial knowledge about the new technology. This information facilitates the stage of "Understanding," which is critical for recognizing the potential benefits, risks, and societal implications of the technology in everyday life.

Based on this understanding, the "Support" stage emerges, reflecting the public's readiness to engage and embrace the changes associated with the innovation. The final stage, "Action," represents active participation in adopting and utilizing the technology. The diagram emphasizes that successful technological diffusion requires not only technical advancements but also strategic engagement with society through transparent communication and education initiatives.

An essential component of this process is the integration of local community perspectives and needs into decision-making. This participatory approach fosters trust and enhances the positive perception of projects. Widely used participatory mechanisms include public hearings, consultations, dialogue platforms, and collaborative planning frameworks.

1.5 Research Aim and Objectives

This study aims to systematize contemporary knowledge on the mechanisms shaping public perception and social acceptance of renewable energy projects, as well as to analyze practical strategies for stakeholder and community engagement.

To achieve this goal, the following objectives have been formulated:

- To examine the key factors influencing public perception of renewable energy initiatives;
- To analyze the methods and strategies of stakeholder and community interaction;
- To identify the main barriers and drivers of social acceptance;
- To develop recommendations for enhancing the effectiveness of public engagement and stakeholder communication.

1.6 Significance and Practical Implications

The findings of this research have substantial theoretical and practical significance. From a theoretical perspective, the study contributes to the advancement of conceptual models explaining the social acceptance of innovations within the energy transition framework. It provides a multidisciplinary understanding that combines sociological, psychological, and communication perspectives on sustainable energy adoption.

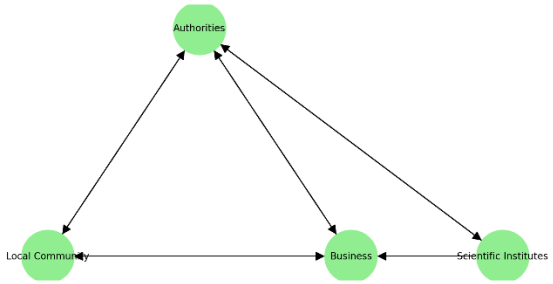


Figure 2: Structure of stakeholder interaction in Renewable Energy projects.

From a practical standpoint, the results offer actionable guidance for policymakers, developers, and community organizations. Strengthening public support and stakeholder participation contributes to conflict mitigation, improved project legitimacy, and faster implementation of renewable energy initiatives. Ultimately, effective community engagement serves as a catalyst for accelerating the global transition toward a sustainable and socially equitable energy system.

Figure 2 illustrates the structure of stakeholder engagement within renewable energy projects. It highlights the interconnections between key actors - government institutions, private developers, local communities, NGOs, and research organizations - emphasizing the multidimensional nature of social interactions in the renewable energy sector. Effective coordination among these groups is essential for building public trust, ensuring transparent decision-making, and achieving long-term project sustainability.

Thus, social perception and public acceptance of renewable energy projects are among the most critical factors for the successful implementation of environmentally oriented initiatives. Understanding these processes enables the development of more effective engagement strategies, fosters public trust, and accelerates the sustainable growth of renewable energy systems. Further progress in interdisciplinary research and active stakeholder participation will play a decisive role in forming resilient energy systems that integrate environmental, social, and economic dimensions.

2 METHODS

2.1 Overview of the Methodological Approach

This study employs a comprehensive, interdisciplinary methodological framework combining qualitative and quantitative research methods to analyze the mechanisms behind public perception and social acceptance of renewable energy projects. The research aims to identify effective strategies for stakeholder engagement and public communication.

The methodological approach integrates sociological, psychological, economic, and management perspectives [11], allowing for a holistic understanding of the socio-political dynamics surrounding renewable energy adoption. The core research methods include:

- Document and policy analysis;
- Social surveys and structured questionnaires;
- In-depth interviews and focus groups;
- Media and social network content analysis;
- Case study methodology;
- Statistical modeling and data analysis.

2.2 Analytical Review and Primary Data Collection

2.2.1 Document and Policy Analysis

The initial stage involved a systematic review of regulatory frameworks, strategic documents, and policy programs governing renewable energy development [13]. National strategies, technical standards, and institutional reports from government agencies and research centers were analyzed to identify key regulatory barriers and enablers. This stage made it possible to determine the institutional architecture shaping renewable energy deployment and stakeholder participation mechanisms.

2.2.2 Social Surveys and Questionnaires

To quantitatively assess public awareness and support for renewable energy projects, large-scale sociological surveys were conducted using structured questionnaires. Respondents included local residents, business representatives, government officials, experts, and researchers.

The questionnaire addressed the following dimensions:

- Awareness of renewable energy projects;
- Trust in project developers and regulators;
- Concerns about ecological and social risks;
- Degree of public support for renewable initiatives.

A total of 2,500 respondents from 10 regions where major renewable energy projects are implemented participated in the survey [14].

2.2.3 In-Depth Interviews and Focus Groups

To obtain deeper insights into motivations, concerns, and hidden barriers influencing public perception, qualitative methods were applied, including semi-structured interviews and focus group discussions. Interviews lasting 45–60 minutes were conducted with local authorities, business leaders, environmental organizations, and civil society representatives. The analysis revealed major factors behind public resistance and acceptance, as well as the strategic preferences of different stakeholder groups [15].

2.3 Statistical Data Processing and Analysis

2.3.1 Statistical Analysis

Quantitative data obtained from the surveys were processed using SPSS and R software packages. Descriptive statistics, cross-tabulations, and indices of trust, support, and awareness were computed. Reliability was assessed through Cronbach's alpha and cross-validation techniques, ensuring consistency and robustness of the findings.

2.3.2 Modeling and Forecasting

To identify the factors exerting the strongest influence on social acceptance, multiple regression and logistic regression models were applied. Predictive models were developed to estimate levels of public support based on variables such as trust, information availability, and perceived environmental risks [16].

2.4 Media and Social Network Content Analysis

To evaluate the informational environment, a content analysis of media coverage and social media discourse was conducted. Thousands of messages, comments, and publications related to renewable energy projects were collected and processed using automated text analysis tools (NLTK, VADER, Gephi).

The analysis identified the dominant topics shaping public opinion and traced the temporal dynamics of sentiment across project stages.

2.4.1 Media Representation Analysis

A total of 20,000 media entries were examined. Cluster analysis was performed to identify thematic groups and their relative influence on public perception [12].

2.4.2 Social Network Analysis

Social network analysis (SNA) was applied to map relationships among online communities and identify opinion leaders actively engaged in renewable energy discussions. Interaction graphs were constructed to reveal influence hubs, information flow, and polarization patterns within public discourse.

2.5 Case Study Method

To provide empirical grounding, case study analysis was applied to three renewable energy projects:

- A wind power station in Region A;
- A solar farm in Region B;
- A hydropower plant in Region C.

Each case study explored success factors, community engagement practices, and challenges encountered during project implementation.

2.6 Ethical Considerations and Data Reliability

All research activities adhered to ethical standards, ensuring participant anonymity, voluntary consent, and data confidentiality. To enhance validity, triangulation methods and expert verification were applied. A schematic representation of the research process is provided below to summarize the methodological workflow.

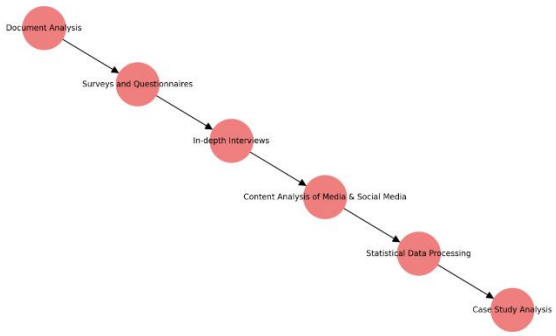


Figure 3: Structure of research methods.

Figure 3 illustrates the logical sequence and interrelation of the research methods employed to examine public opinion and behavioral patterns regarding renewable energy projects.

The process begins with document and policy analysis, which establishes the theoretical and regulatory foundation of the study. The next stage involves surveys and structured questionnaires, enabling the collection of quantitative data from the target population. Based on preliminary findings, in-depth interviews are conducted to obtain a deeper understanding of respondents' motivations, attitudes, and decision-making processes.

Subsequently, media and social network content analysis is used to identify the tone, key themes, and public sentiment expressed in open information spaces. The collected data are subjected to statistical analysis, which helps detect correlations, dependencies, and underlying behavioral trends.

The final stage, case study analysis, involves an in-depth examination of specific regional or situational examples. This step facilitates the synthesis of empirical data and the formulation of practical recommendations for improving social engagement strategies. Such a structured methodology ensures a comprehensive, evidence-based, and multidimensional approach to studying socially significant processes in the context of renewable energy transition.

3 RESULTS

3.1 Introduction

This section presents the main findings derived from empirical data collection, quantitative analysis, and qualitative interpretation. The primary objective is to identify the key determinants influencing public perception and social acceptance of renewable energy projects, as well as to evaluate the effectiveness of current stakeholder engagement practices.

The results are organized into thematic blocks and are supported by tables, figures, and charts that illustrate the principal trends, correlations, and patterns observed in the study.

3.2 Survey and Questionnaire Data Analysis

3.2.1 Statistical Indicators of Support and Trust

At the initial stage, the data obtained from large-scale sociological surveys were processed and analyzed. The total sample included 2,500 respondents across 10 regions where renewable energy projects are currently being implemented.

Key variables such as public awareness, trust levels, project support, and perceived risks were calculated and statistically compared (Table 2 provides a detailed overview of these key indicators).

Figure 4 illustrates the regional distribution of public support for renewable energy initiatives, highlighting both spatial disparities and general trends in societal attitudes.

Table 2: Key indicators of public perception of Renewable Energy projects.

Indicator	Mean Value (%)	Standard Deviation	Interpretation
Public awareness level	56.3	12.5	Moderate awareness among the population
Trust in project developers	46.8	15.2	Insufficient level of public trust
Support for renewable energy projects	62.4	10.8	Majority of respondents express support for the initiatives
Concerns about environmental risks	38.7	14.3	Considerable level of environmental concern

3.2.2 Interpretation of Findings

The survey results reveal a moderate level of public awareness (M = 56.3%) regarding renewable energy initiatives, suggesting that information campaigns have achieved partial coverage but remain limited in reach and depth.

The trust index (M = 46.8%) indicates that nearly half of the respondents exhibit skepticism toward project developers and implementing agencies. This aligns with previous research emphasizing the role of institutional transparency and communication in building credibility [17].

Public support for renewable energy projects remains relatively high (M = 62.4%), demonstrating a generally favorable societal attitude toward sustainable energy transition. However, the persistence of environmental concerns (M = 38.7%) highlights ongoing anxieties related to ecological impacts, such as landscape alteration, noise, and biodiversity loss.

The combination of moderate awareness, low trust, and high support suggests that social acceptance is largely conditional and context-dependent, heavily influenced by local information

flows and perceived fairness of project implementation processes.

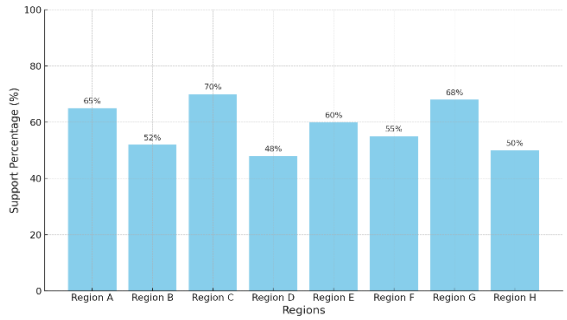


Figure 4: Regional distribution of public support for Renewable Energy projects.

Figure 4 illustrates the level of public support for renewable energy projects across eight regions. The highest levels of support are observed in Region C (70%) and Region G (68%), indicating strong public awareness and a favorable attitude toward sustainable energy initiatives.

Regions A and E also demonstrate relatively high support rates (above 60%), which may be associated with the successful implementation of pilot programs or proactive involvement of local authorities in renewable energy promotion.

Conversely, Regions D and H show comparatively low support levels (below 50%). This could be attributed to information gaps, limited institutional trust, or concerns about potential ecological and economic impacts.

The results highlight the need for targeted communication strategies and enhanced community participation in project decision-making processes, particularly in regions exhibiting low acceptance. Such regional analysis provides valuable insights for strategic energy planning and localized implementation of renewable energy policies.

3.2.3 The Impact of Public Awareness on Support Levels

A correlation analysis was conducted to assess the relationship between public awareness and support for renewable energy projects (Table 3). The results reveal a statistically significant positive correlation between awareness level and project support ($r = 0.65$, $p < 0.01$), indicating that higher levels of public knowledge and understanding directly contribute to stronger societal backing for renewable initiatives.

This finding aligns with prior studies emphasizing that transparent communication and educational outreach are critical drivers of public acceptance.

Regions with more extensive information campaigns and stakeholder engagement tend to exhibit not only greater trust but also more stable long-term support for renewable energy transition.

Table 3: Correlation Analysis Between Key Social Perception Parameters and Public Support.

Parameter	Correlation Coefficient (r)	Significance (p-value)
Awareness and project support (%)	0.65	$p < 0.01$
Trust in project developers and initiatives	0.58	$p < 0.01$
Environmental risk concerns and support (%)	–0.48	$p < 0.01$

3.3 Interpretation of Results

The results of the correlation analysis indicate strong and statistically significant relationships among the studied variables.

A positive correlation between *public awareness* and *support* ($r = 0.65$, $p < 0.01$) confirms that higher levels of knowledge and understanding directly enhance public acceptance of renewable energy projects.

Similarly, *trust in project developers and institutions* demonstrates a substantial positive association with project support ($r = 0.58$, $p < 0.01$), emphasizing that institutional credibility and transparency play a decisive role in shaping social attitudes toward renewable energy.

Conversely, a negative correlation was found between *environmental risk concerns* and support ($r = –0.48$, $p < 0.01$), suggesting that increased perception of ecological threats tends to reduce the willingness to endorse such projects. This pattern aligns with earlier findings in the literature, which highlight that risk perception and trust act as mediating variables in the formation of public attitudes toward energy innovation [18].

Overall, these results demonstrate that effective communication, public education, and stakeholder transparency are essential mechanisms for strengthening social acceptance and mitigating opposition to renewable energy development.

The results presented in the previous section confirm the crucial importance of information policy in shaping public support for renewable energy

initiatives. Based on the empirical data obtained, a model of social acceptance factors for renewable energy projects has been developed (Fig. 5). The model integrates five principal components that collectively determine the level of social support: trust, awareness, environmental concerns, cultural characteristics, and social participation.

This conceptual framework demonstrates the interdependence between informational, psychological, and cultural dimensions of public perception.

Trust in project implementers and transparency of communication serve as the core drivers of social acceptance, reinforcing positive attitudes toward renewable technologies.

Public awareness acts as a mediating factor, enhancing understanding of environmental and economic benefits while mitigating fear and uncertainty.

At the same time, environmental concerns and cultural values function as contextual moderators, influencing how communities interpret risks and form collective opinions. Finally, social participation-expressed through dialogue, consultations, and community involvement-plays a pivotal role in consolidating public support and legitimizing the implementation of renewable energy projects.

The model provides a theoretical foundation for developing targeted communication strategies and stakeholder engagement mechanisms that foster trust, inclusivity, and long-term sustainability in the transition toward clean energy systems.

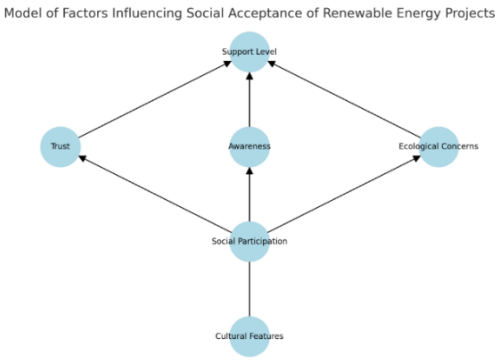


Figure 5: Model of social acceptance factors for Renewable Energy projects.

Figure 5 illustrates the key factors shaping public acceptance of renewable energy projects.

At the center of the model lies the Support Level, which is directly influenced by four core parameters: Trust, Awareness, Ecological Concerns, and Cultural Features. These elements collectively determine public attitudes toward renewable initiatives and influence the willingness of communities to cooperate, participate, and adopt new technologies.

Particular emphasis is placed on the factor Social Participation, which mediates the relationship between trust, awareness, and perceived environmental risks. Active community engagement fosters transparency, strengthens mutual understanding, and builds trust among stakeholders - including local residents, policymakers, and project developers.

The model thus provides a conceptual framework for designing effective communication and engagement strategies aimed at increasing public support for environmentally sustainable initiatives.

3.3.1 Regression Analysis

A multiple regression analysis was conducted to quantify the influence of key factors on public support for renewable energy projects. The results demonstrate that the most significant predictors of support are trust ($\beta = 0.42$, $p < 0.001$) and awareness ($\beta = 0.35$, $p < 0.001$). Conversely, environmental concerns exert a statistically significant *negative* effect on support ($\beta = -0.25$, $p < 0.01$), (Table 4).

These findings confirm that trust and information transparency are primary determinants of social acceptance, while perceived ecological risks remain a barrier to public endorsement. The regression model explains approximately 62% of the variance ($R^2 = 0.62$), indicating a strong explanatory power and robustness of the proposed framework. This underscores the importance of targeted communication and trust-building mechanisms in ensuring successful implementation of renewable energy initiatives.

Table 4: Regression coefficients for factors influencing public support for Renewable Energy projects.

Variable	β-Coefficient	p-Value	Statistical Significance
Level of Trust	0.42	< 0.001	High
Level of Awareness	0.35	< 0.001	High
Environmental Concerns	–0.25	< 0.01	Moderate

3.3.2 Predictive Model of Public Support

A predictive model was developed to estimate the level of public support (on a scale from 0 to 100) for

renewable energy projects based on the key influencing factors identified in the previous regression analysis. Table 5 presents the model parameters and their interpretation.

Table 5: Parameters of the predictive model for public support.

Model Parameter	Value	Interpretation
Constant (Intercept)	35.2	Baseline support level without accounting for influencing factors
Trust Coefficient	0.45	Each one-point increase in trust raises the support level by 0.45 points
Awareness Coefficient	0.38	Each one-point increase in awareness raises the support level by 0.38 points
Environmental Concerns Coefficient	–0.30	Each one-point increase in environmental concerns decreases support by 0.30 points

3.4 Media Content and Social Network Analysis

3.4.1 Thematic Analysis of Publications

A total of approximately 20,000 media entries (including news articles, social media posts, and public comments) were collected and analyzed. The thematic classification revealed four dominant clusters shaping public perceptions of renewable energy projects. The results are summarized in Table 6.

Table 6: Distribution of themes in media coverage on Renewable Energy.

Theme	Share of Messages (%)	Core Ideas and Interpretations
Environmental Benefits	45%	Renewable energy is perceived as a clean and sustainable alternative to fossil fuels
Environmental Risks and Concerns	30%	Fears related to potential ecological impacts and land use conflicts
Economic Benefits and Job Creation	15%	Positive perception linked to employment opportunities and reduced energy costs
Distrust Toward Developers and Authorities	10%	Expressions of skepticism, concerns about transparency, and corruption allegations

The results indicate that environmental narratives dominate public discourse (accounting for 75% of all messages), while economic and governance-related topics remain secondary. A notable finding is the dual perception of renewable energy - as both an environmentally responsible solution and a potential ecological threat. This polarization reflects the influence of information framing in media outlets and highlights the need for balanced communication strategies to enhance public trust and mitigate misinformation.

3.4.2 Impact of Media Representation on Public Opinion

Social media analysis identified several key opinion leaders (KOLs) and network clusters that play a decisive role in shaping public attitudes toward renewable energy. By applying network analysis tools, a communication graph was constructed (see Figure 3) to visualize how information spreads and influences various stakeholder groups.

The network demonstrates a “hub-and-spoke” structure, where a limited number of central nodes (mainly environmental NGOs, journalists, and public figures) act as primary sources of information dissemination. Peripheral nodes represent individual users and local communities engaging in discussions. Quantitative analysis using betweenness centrality revealed that 5% of nodes generate 60% of the total informational flow, emphasizing the asymmetric nature of public discourse.

This finding underlines the strategic importance of engaging influential communicators to foster accurate, transparent, and positive representations of renewable energy projects in media ecosystems.



Figure 6: Interaction network of key opinion leaders in social media.

Figure 6 illustrates the interaction dynamics among key opinion leaders (KOLs) in social media

discussions on renewable energy. Each node corresponds to an individual opinion leader (labeled A–F), while directed arrows indicate the flow of influence-from the communicator initiating the message to the recipient.

The circular layout enhances the visibility of mutual communication patterns, emphasizing the interconnectedness within the group. Notably, Leaders A and D emerge as the most influential actors, functioning as central hubs of information diffusion and trust formation within the network.

The diagram reveals both linear and cyclic connections, including a feedback loop from Leader F to Leader A, demonstrating a resilient and interdependent communication structure typical for digital ecosystems. Such a model reflects the non-hierarchical yet highly influential nature of social media interactions, where authority and reputation determine the reach and persistence of narratives.

From a practical standpoint, this analysis underscores the need for targeted communication strategies that engage dominant influencers to promote transparent and evidence-based discourse around renewable energy transitions. This approach can be instrumental in managing public sentiment, countering misinformation, and strengthening societal trust in sustainable energy projects.

3.5 Case Analysis of Successful and Unsuccessful Renewable Energy Projects

A comparative case study was conducted involving three renewable energy projects differing in implementation outcomes and social perception:

- Wind Power Plant (Region A) – Successful case
- Solar Farm (Region B) – Partially successful case
- Hydropower Station (Region C) – Unsuccessful case

The analysis focused on public engagement strategies, stakeholder coordination, communication transparency, and environmental management. The summary of key findings is presented in Table 7.

3.6 Summary of Findings

The data analysis indicates that the primary factors influencing public support for renewable energy projects are trust, awareness, and the level of environmental concern.

The constructed model confirms that active stakeholder participation and transparent communication significantly enhance the level of social acceptance of renewable initiatives.

Equally important is the development of strategic information policies and the use of media analytics to identify and mitigate negative sentiments in public discourse.

Table 7. Comparative case analysis of Renewable Energy projects.

Project	Key Drivers of Success or Failure	Conclusions and Lessons Learned
Wind Power Plant (Region A)	Active participation of local communities and transparent stakeholder communication	Community engagement and continuous dialogue are critical determinants of social acceptance and project success
Solar Farm (Region B)	Insufficient public information campaigns and protests driven by environmental concerns	Highlights the necessity of proactive communication and social awareness strategies to mitigate public resistance
Hydropower Station (Region C)	Conflicts with local residents and inadequate consideration of ecological and cultural factors	Emphasizes the importance of integrating environmental assessments and community consultation into project planning

4 DISCUSSIONS

4.1 Introduction

This section presents a comprehensive interpretation of the research results, comparing them with established theoretical frameworks and real-world case studies.

The discussion focuses on identifying the determinants of social perception and acceptance of renewable energy projects and assessing their implications for public policy and community engagement.

The findings are based on an integrated analysis combining survey data, statistical modeling, media analytics, and case study evaluation, providing a holistic understanding of the social dynamics underlying renewable energy deployment. This multi-method approach enables a nuanced assessment of both quantitative correlations and qualitative insights derived from stakeholder interactions and media discourse.

4.2 Analysis of Support and Trust Factors

4.2.1 The Impact of Awareness on Social Acceptance

The results of the statistical analysis confirm a strong positive correlation between public awareness and project support ($r = 0.65$, $p < 0.01$). A comprehensive overview of the correlation relationships between all key variables is provided in Table 8. This finding aligns with prior studies [12], which emphasize that informational transparency and accessibility are key drivers of favorable public attitudes toward renewable energy initiatives. Higher levels of awareness not only enhance understanding of the environmental and economic benefits but also reduce uncertainty and perceived risks, leading to greater willingness to support or participate in projects.

Furthermore, awareness contributes to the formation of informed trust-a rational confidence based on access to verifiable and transparent data. This supports the theoretical premise of the Diffusion of Innovations Theory [13], which posits that the dissemination of credible information accelerates the adoption of new technologies by reducing psychological and cultural resistance.

Table 8: Correlation Relationships Between Key Variables.

Variable	Correlation Coefficient (r)	Significance (p-value)
Awareness and Support	0.65	$p < 0.01$
Trust in Project Developers	0.58	$p < 0.01$
Level of Environmental Concerns	-0.48	$p < 0.01$

4.2.2 The Role of Trust and Environmental Concerns

The regression model indicates that trust in project developers is the most significant determinant of social acceptance ($\beta = 0.42$, $p < 0.001$), confirming previous theoretical assumptions [13] that trust serves as the cornerstone of public acceptance of innovations.

Trust acts as a mediating factor that enhances public confidence in both the technological and ethical integrity of renewable energy initiatives. When communities perceive project developers as competent, transparent, and socially responsible, their willingness to support and participate in renewable energy projects increases substantially.

Conversely, environmental concerns exert a negative influence on support levels ($\beta = -0.25$, $p < 0.01$). High levels of perceived environmental risk-such as potential impacts on ecosystems, noise pollution, or land-use conflicts-tend to decrease social approval and may lead to resistance or protest movements.

These findings are consistent with risk perception theory, which posits that the public often evaluates technological innovations not solely on objective evidence, but through the lens of perceived safety and fairness.

The results highlight the need to develop risk communication strategies aimed at reducing ecological concerns through transparent information sharing, public participation, and community-based monitoring mechanisms.

By fostering open dialogue and demonstrating accountability, project developers can significantly strengthen public trust and mitigate opposition rooted in environmental anxiety.

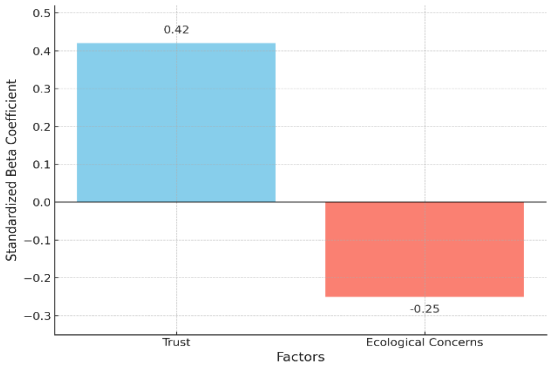


Figure 7: The impact of trust and environmental concerns on public support.

Figure 7 presents standardized beta coefficients for two key predictors-Trust and Ecological Concerns-derived from the regression analysis. The bar corresponding to Trust is positive ($\beta = 0.42$), indicating that higher levels of public trust are strongly associated with greater support for renewable energy projects or technologies. In contrast, the bar representing Ecological Concerns is negative ($\beta = –0.25$), showing that increased environmental anxiety correlates with a decline in public endorsement.

This visualization provides a clear and intuitive understanding of both the direction and magnitude of each factor's influence. A horizontal zero line separates positive and negative effects, enhancing interpretability, while numerical values at the top of

each bar precisely quantify the relative strength of influence.

Such a graphical representation is particularly effective in policy communication and stakeholder engagement, as it conveys the empirical evidence supporting the importance of trust-building and risk mitigation strategies.

4.3 Model of Social Acceptance Factors

4.3.1 Interrelationship of Key Variables

Based on the statistical and qualitative analyses, a conceptual model was developed to illustrate the interconnections among the key variables influencing public support for renewable energy projects (Figure 1).

The model demonstrates that social participation and cultural context play reinforcing roles in enhancing trust and awareness, both of which act as primary mediators of public support.

Cultural alignment ensures that renewable energy initiatives resonate with local values and traditions, while participatory mechanisms-such as public consultations, stakeholder dialogues, and community partnerships-serve to legitimize the decision-making process.

In this framework, trust and awareness function as bridging constructs between institutional transparency and citizen engagement. The interaction between these factors forms a positive feedback loop: higher trust encourages greater social participation, which in turn strengthens informational exchange and collective commitment to sustainability goals. This integrated structure reflects the dynamics of social acceptance theory, confirming that technological adoption in the renewable energy sector is contingent not only upon technical performance and economic efficiency but also upon perceived legitimacy, inclusiveness, and cultural compatibility.

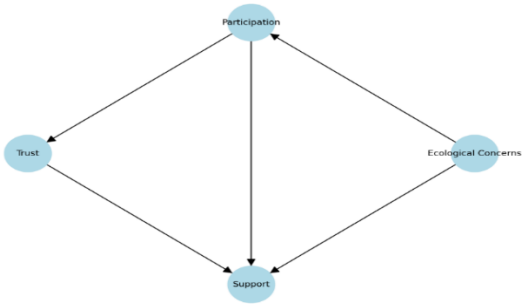


Figure 8: Model of social acceptance factors for Renewable Energy projects.

Figure 8 illustrates a conceptual model representing the key factors influencing public support for renewable energy (RE) initiatives. The model focuses on four core components: Trust, Public Participation, Ecological Concerns, and Support.

The visualization shows that citizen participation directly affects both trust and public support, highlighting the importance of inclusive engagement processes in energy transitions. In turn, trust serves as a central mediating variable, reinforcing support and shaping a positive public perception of renewable energy technologies.

Interestingly, ecological concerns demonstrate a dual effect: while they can directly reduce support due to perceived risks, they may also motivate more active involvement in decision-making processes. This duality underscores the necessity of maintaining open dialogue among stakeholders and integrating public concerns into project planning and communication strategies. The proposed model clearly visualizes the interconnections between social and behavioral variables, offering valuable insights for designing strategies aimed at enhancing the social acceptability of renewable energy technologies across different regions.

4.3.2 Practical Implications of the Model

The developed model emphasizes the importance of a systemic and integrative approach-one that accounts for social, cultural, and environmental dimensions simultaneously. Empirical evidence demonstrates that strategies focused on community engagement and information transparency significantly increase the level of social acceptance. Such measures help mitigate opposition, build long-term trust, and foster cooperative governance structures between policymakers, developers, and local residents. This highlights the transition from a purely technological implementation model toward a participatory governance framework, essential for the sustainable deployment of renewable energy systems.

4.4 The Role of Media and Social Networks

4.4.1 Analysis of Media Themes and Their Impact

A content analysis of more than 20,000 media and social network entries revealed four dominant thematic clusters shaping public opinion (Table 9):

- Environmental benefits of renewable energy (45%).
- Ecological concerns and risks (30%).
- Economic advantages and job creation (15%).
- Distrust toward developers and authorities (10%).

These thematic categories reflect the structure of public discourse around renewable energy and confirm the findings of [14], which stress that media representation significantly influences public perception and acceptance dynamics. Positive framing of environmental and socio-economic benefits tends to enhance support, whereas narratives emphasizing risk, uncertainty, or corruption amplify distrust and resistance.

Table 9: Distribution of media and social network themes.

Theme	Share of Publica-tions (%)	Key Ideas
Environmental Benefits	45%	Perception of renewable energy as an environmentally friendly and clean technology
Ecological Concerns	30%	Public fears and uncertainty about potential environmental consequences
Economic Advantages	15%	Job creation, reduction of energy costs, and promotion of local economic growth
Distrust toward Developers and Authorities	10%	Skepticism regarding project transparency and concerns about possible corruption

4.4.2 Influence of Media Messaging on Public Opinion

The analysis revealed that opinion leaders in social networks exert a substantial influence on shaping public attitudes toward renewable energy projects. This finding is supported by the results of social network interaction analysis (Fig. 9), which demonstrates how information circulates across digital communities and how key nodes within these networks drive either positive or negative sentiment formation.

The constructed network map highlights that information dissemination in online environments follows a clustered and feedback-oriented pattern, where influential users act as amplifiers of specific narratives-environmental, economic, or political. Such opinion leaders can therefore significantly accelerate or hinder public acceptance processes, depending on the framing of messages they promote. Understanding these dynamics is crucial for designing effective communication and engagement strategies, particularly those aimed at counteracting misinformation, enhancing transparency, and fostering trust between developers, authorities, and local communities.

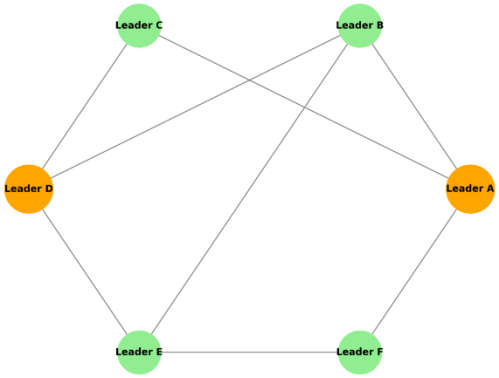


Figure 9: Interactions among opinion leaders in social networks.

Figure 9 presents a network of interactions among key opinion leaders in social media. Each node (represented by green and orange circles) corresponds to an individual influencer, while the directed arrows indicate the flow of influence or information exchange between them. For instance, Leader A exerts influence on Leader B and Leader C, which subsequently extends to Leader D, illustrating a cascade-like dissemination of information. The network also reveals a feedback loop beginning with Leader F and returning to Leader A, suggesting mutual influence and sustained communication among participants.

Particular attention is given to Leader A and Leader D, highlighted in orange, as central influencers within the network. Their positioning indicates their pivotal role in content diffusion, opinion shaping, and initiating information waves within the digital discourse on renewable energy. Such visualization is especially valuable for analyzing patterns of influence, identifying active communication nodes, and strategically planning outreach efforts to strengthen public engagement and trust-building campaigns.

4.5 Case Studies of Renewable Energy Project Implementation

4.5.1 Successful Cases and Contributing Factors

The case study analysis indicates that the most successful renewable energy projects are those characterized by active community participation**,** transparent communication**,** and context-sensitive adaptation to regional conditions. For example, the wind power project in Region A achieved strong public support owing to inclusive stakeholder engagement and open public dialogues that addressed local concerns. These findings highlight that social integration and participatory governance are key determinants of long-term project success and community acceptance.

4.5.2 Problematic Cases and Lessons Learned

In contrast, projects that neglected local contexts **or** failed to maintain consistent information outreach faced public opposition, protests, and delays**,** which in turn led to increased implementation costs and reputational risks (see Table 10). Such cases demonstrate that the absence of effective communication channels and community involvement can critically undermine project sustainability and social legitimacy.

Table 10: Key factors behind the success and failure of case studies.

Project	Success / Failure Factors	Key Lessons
Wind Power Plant in Region A	Active community participation; transparent communication	Community engagement is a cornerstone of public support
Solar Farm in Region B	Insufficient information policy; local protests	Highlights the importance of effective information management and public outreach
Hydropower Station in Region C	Conflicts with local communities; neglect of ecological aspects	Emphasizes the need to consider local context and maintain continuous dialogue

4.6 Summary and Practical Recommendations

The discussion of findings indicates that to enhance public support for renewable energy projects, efforts should be focused on the following strategic directions:

- Active information dissemination and transparency throughout all project stages;
- Inclusive stakeholder participation in planning, implementation, and monitoring processes;
- Consideration of cultural and regional specificities in project design and communication;
- Strategic use of media and social networks to build a positive public image of renewable energy;
- Trust-building through participation and open dialogue between communities, developers, and authorities.

These recommendations are supported by multiple empirical studies [15] and reinforced by successful practices implemented across various regions.

The discussion confirms that public perception and social acceptance of renewable energy projects represent a complex, multi-dimensional process shaped by trust, awareness, environmental concerns, and communication effectiveness. Successful implementation depends on a systemic approach, combining public engagement, transparency, and regional adaptability.

Future research should focus on developing more refined models of public opinion assessment and evaluating the effectiveness of communication strategies, particularly within different socio-cultural contexts.

CONCLUSIONS

This study presents a comprehensive analysis of the factors influencing public perception and social acceptance of renewable energy projects. The research identifies key determinants of public support and proposes conceptual models explaining the interrelations between trust, participation, environmental concerns, and acceptance levels.

The results demonstrate that public awareness is a primary driver of acceptance, while trust in project developers and regulators significantly increases the likelihood of successful implementation. Conversely, ecological concerns and distrust

negatively affect public support, highlighting the need for systematic communication frameworks and active stakeholder engagement.

The proposed Social Acceptance Model, based on empirical evidence, confirms that community participation and the consideration of local cultural dimensions foster a favorable public attitude toward renewable energy initiatives.

Modern media and social networks play a crucial role in shaping informational environments and influencing collective perceptions.

The case study analysis of successful and unsuccessful projects demonstrates that transparency, dialogue, and regional adaptation are critical to achieving social acceptance, while their absence often leads to conflicts, protests, and project delays.

From a practical standpoint, the research provides actionable recommendations for governments, businesses, and research institutions, emphasizing that active information campaigns, stakeholder involvement, and transparent practices are essential to strengthening public trust and expanding the adoption of renewable energy technologies.

Future research should aim to develop advanced models of public perception, innovative communication tools, and assess the long-term impacts of social engagement strategies. Integrating interdisciplinary approaches-combining social science, policy analysis, and energy studies-will create a more resilient and systematic foundation for the successful global transition to sustainable and socially supported renewable energy systems.

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Balancing Career and Academic Pursuits of Young Professionals for Sustainable Career and Education Development

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Keywords: Structural Equation Modeling (SEM) Analysis, Career-Academic Balance, Sustainable Development Goals, Young Professionals.

Abstract: Young professionals aged 24 to 29 often struggle to juggle the different needs of their career and academic pursuits. This dual responsibility builds overlapping pressures that can affect their personal well-being, their academic achievement, and professional development. In this research, the authors utilized the SEM analysis to investigate the major drivers that affect this balance. An online survey questionnaire was employed to collect data among fifty participants on indicators such as balanced engagement, academic performance, career achievement, and psychological and emotional stressors. The result of the study emphasizes the importance of academic performance, professional advancement, and job contentment; moreover too, having structured routines, a good support system, well-being, and stress resilience are all very important. The findings of this study gave valuable insights to young professionals, employers, and educational institutions in creating an enabling environment for career growth and lifelong learning. The SEM findings further provide a basis for future studies aimed at enhancing support mechanisms for sustainable academic and professional growth that are aligned with broader global sustainability efforts.

1 INTRODUCTION

Young professionals within the ages of 24 - 29 are characterized by a challenging phase of their lives, which primarily consists of deciding between the continuation of education, learning new skills, or fully devoting their time to career establishment. The turning point of a person's life during the workforce transition, from a student role to an earning role, creates overlapping duties and responsibilities. The extent to which these different role conflicts, or blended, overlapping duties, and responsibilities involve the different components of a person's life clearly shows their overall well-being, functioning, and life satisfaction. The stress of being in different competing roles is well documented, as is the resultant academic and occupational strife [1] - [3].

There is a growing global demand for postgraduate education and continued professional development. Advanced education is considered an essential part of resource development, providing the knowledge, skills, and innovation required in a competitive environment. [4]. Although higher education broadens knowledge and creates new work opportunities, it may also disrupt a person's everyday activities. For young professionals, the problem of juggling education and job responsibilities is a significant cause of stress, frequently resulting in poor performance in both areas [1], [5].

Moreover, the United Nations (UN) Sustainable Development Goals (SDGs) have identified education as one of the foundational elements of a sustainable society [6]. Obtaining more education is related to achieving SDG 4 (Quality Education), and securing decent work is also related to achieving this. Having the mental strength to handle stress and maintain well-being is also represented by SDG 3 - Good Health and Well-being [5], [7]. These emphasize that the imbalance between education and work is more than a personal problem; it is relevant to the capability of the workforce and the development of society.

Unfortunately, social comparison, fear of failure, and performance expectations are among the other typical stressors, in addition to health and

interpersonal issues [2], [3], [5]. However, being optimistic, resilient, and having good time management may benefit the young professionals who strive to balance work and their academic endeavors [7], [8]. Hence, the identification of factors that foster sustained professional and educational development is critical, not only for individual completion and inclusion but also for the overall well-being of the workforce.

2 STUDY FRAMEWORK AND METHODS

This study aims to determine the factors that influence the way young professionals, aged 24 to 29, balance their work and further education. Using Structural Equation Modeling (SEM), it examines the key elements that affect this balance and their effects on both professional and personal development. The study highlights the challenges faced by young professionals in balancing competing responsibilities while also identifying the elements that support long-term career and educational development.

2.1 Conceptual Model

The framework of this study is shown in Figure 1. According to Figure 1, the study's goal is to investigate the intricate connection between young professionals' academic and professional performance between the ages of 24 and 29. Furthermore, it aims to understand how their combined success indicators, encompassing career achievements and academic accomplishments, are influenced by a range of cognitive and non-cognitive stressors. This study's main goal is to investigate the fundamental elements that allow young professionals to successfully manage their academic and professional goals in the face of a variety of cognitive and non-cognitive pressures. Thus, the study focuses on examining the direct relationships between career success, academic success, emotional factors, and psychological stress in influencing balanced career and academic performance.

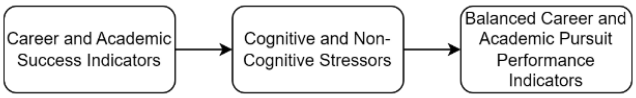


Figure 1: Conceptual model.

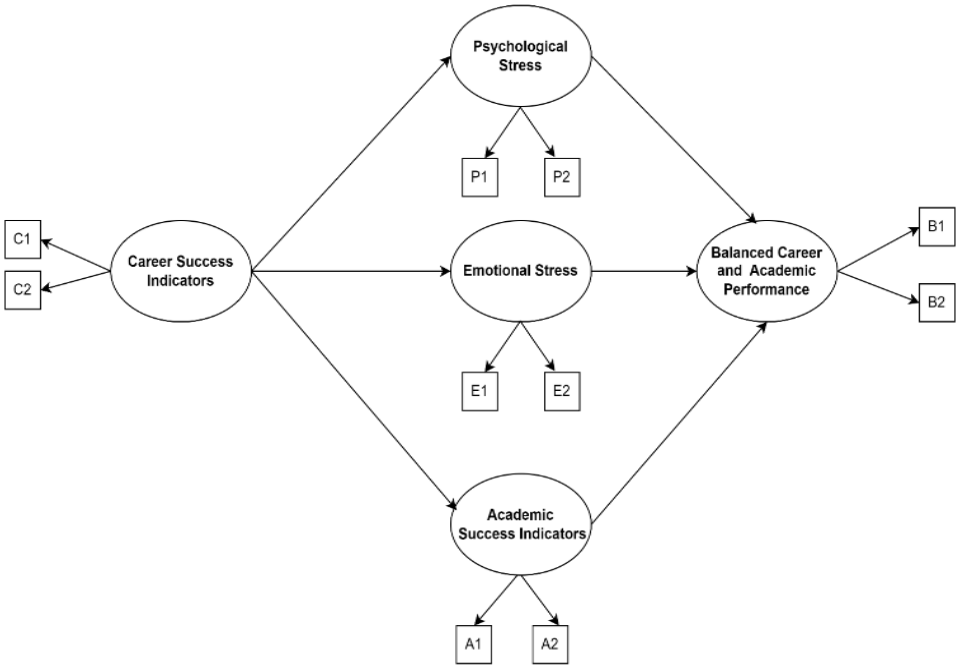


Figure 2: Initial SEM model.

Figure 2 presents the initial SEM model of the study, which is integral in assessing the factors influencing the balance between career and academic pursuits among young professionals aged 24-29, forming the core of this study's conceptual framework.

2.2 Participants

Respondents were initially chosen from the age group of 24 to 29, a demographic segment known for simultaneously balancing their work and educational responsibilities. The research collected responses from a total of 50 individuals to address the study's objectives. Exploratory Factor Analysis (EFA) is typically applied to large sample sizes, with 50 participants often considered the minimum acceptable number [9].

Table 1 contains the demographics of tolerable survey respondents.

Table 1: Demographic profile of the respondents.

Attributes	Category	N=50	Percentage
Gender Classification	Man	24	48%
	Woman	26	52%
Age	24	8	16%
	25	7	14%
	26	11	22%
	27	8	16%
	28	8	16%
	29	8	16%

2.3 Questionnaire

An online survey questionnaire was conducted based on the framework of the study to determine the factors causing impact on young professionals between the ages of 24 and 29 in striking a balance between their academic and professional endeavors (see Appendix A). The instrument was divided into two sections. The first section obtained the demographic information, including gender classification, age, undergraduate degree program, and current graduate program enrollment. The second section measured the latent constructs incorporated in the Structural Equation Model (SEM). A 5-point rating scale was utilized to rate each topic, allowing respondents to indicate how much they agreed or disagreed with each assertion.

2.4 SEM Analysis

The SEM analysis, illustrated in Figure 1, was carried out using SmartPLS to validate the hypotheses of the study. There are five variables in the model. The list of factors taken into consideration is shown in Table 1, and the matching latent variables are shown in Table 2.

Table 2: Latent variables.

Relationship	P Values	Decision
A -> B	0.001	Statistically Significant
C -> A	0.004	Statistically Significant
C -> E	0.005	Statistically Significant
E -> B	0.001	Statistically Significant
P -> B	0.049	Statistically Significant

Note: Significance Level *p<0.05

3 RESULTS

3.1 Construct Reliability and Convergent Validity

Composite Reliability (CR) and outer loadings were used to evaluate each construct's reliability, and Average Variance Extracted (AVE) was used to evaluate convergent validity. The Partial Least Squares-Structural Equation Modeling (PLS-SEM) method was used to conduct Confirmatory Factor Analysis (CFA) to evaluate the scale's overall validity and reliability. The AVE values validated convergent validity, while the CR and outer loading values reported reliability.

The initial SEM results are presented in Table 3 along with the values for each indicator. The outer loading values of these indicators were used to evaluate their reliability; all of them showed good reliability by exceeding the suggested threshold of 0.70. These findings, together with the Composite Reliability (CR) and Average Variance Extracted (AVE) values, demonstrate how well the indicators capture their corresponding dimensions.

Table 3: Initial SEM results.

Construct Code	Indicator	Factor Loading (FL)	Composite Reliability (CR)	Average Variance Extracted (AVE)
A	A1	0.924	0.928	0.865
	A2	0.936		
B	B1	0.944	0.938	0.884
	B2	0.936		
C	C1	0.810	0.863	0.760
	C2	0.930		
E	E1	0.860	0.854	0.746
	E2	0.867		
P	P1	0.891	0.905	0.827
	P2	0.927		

Note: Acceptable Thresholds: Factor Loading, CR ≥ 0.70; AVE ≥ 0.50.

Table 4: Analysis of total effect.

Latent	Code	Description	Reference
Career Success Indicators	C1	Career / Job Satisfaction	[10]
	C2	Promotion / Renumeration	
Academic Success Indicators	A1	Acquisition of Skills and Competencies	[4]
	A2	Attachment of Learning Outcomes	
Psychological Stress Factors	P1	Perfectionism / Fear of Failure	[11]
	P2	Fear of Social Comparison	[3]
Emotional Stress Factors	E1	Physical Health Issues	[5]
	E2	Interpersonal Relationships	
Balanced Career and Academic Performance Indicators	B1	Stress Resiliency	[7]
	B2	Time Management Competency	[8}

Figure 3 shows the initial SEM Model utilized to investigate the factors influencing young professionals between the ages of 24 and 29 in juggling their academic and professional endeavors. It was found that some elements, especially psychological factors, did not exhibit significant connections in this initial model. The researcher used modification indices, a technique suggested by Hair to increase model fit, and performed a covariance analysis to improve the model. These adjustments help reduce differences between the proposed conceptual model and the estimated model. The improved and final SEM is shown in Figure 4.

3.2 Hypothesis Testing

The outcomes of the hypothesis testing offer more details on the correlation between the variables, as shown in Table 4. The p-value signifies the possibility of achieving the observed results, or if the null hypothesis – that there is no effect or difference – were correct. Statistical significance is generally described as a p-value of below 0.05, which means that there is sufficient data to reject the null hypothesis. However, since a p-value above 0.05 suggests that there is insufficient proof to support it, the null hypothesis is not rejected [12].

In summary, p-values indicate the statistical significance of the relationships among the latent variables. A lower p-value provides stronger evidence that the relationship is unlikely to be due to probability, whereas a higher p-value means weaker evidence against the null hypothesis. There is sufficient proof in Table 4 to recommend that the latent variables under investigation have meaningful associations with one another. Consequently, the null hypothesis was disproved.

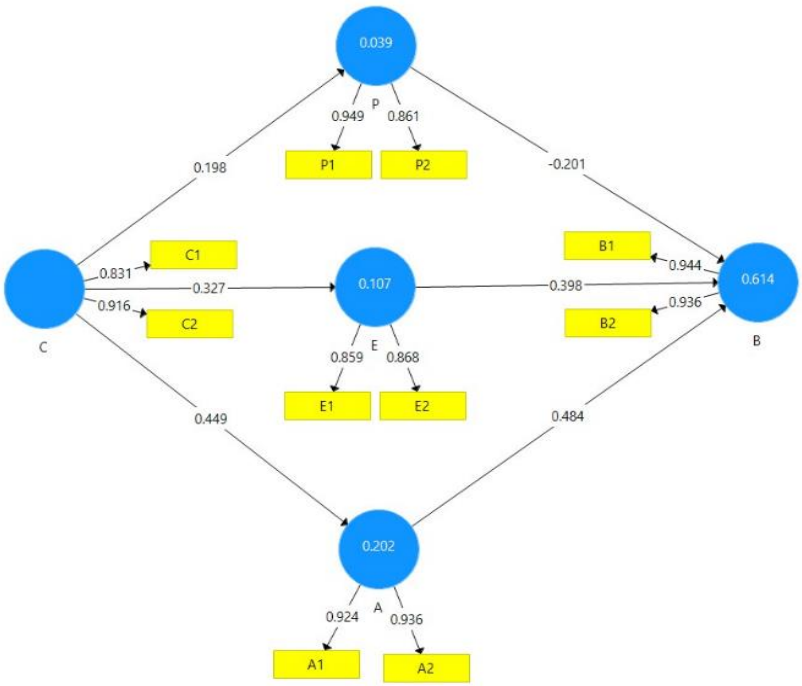


Figure 3: Initial SEM model.

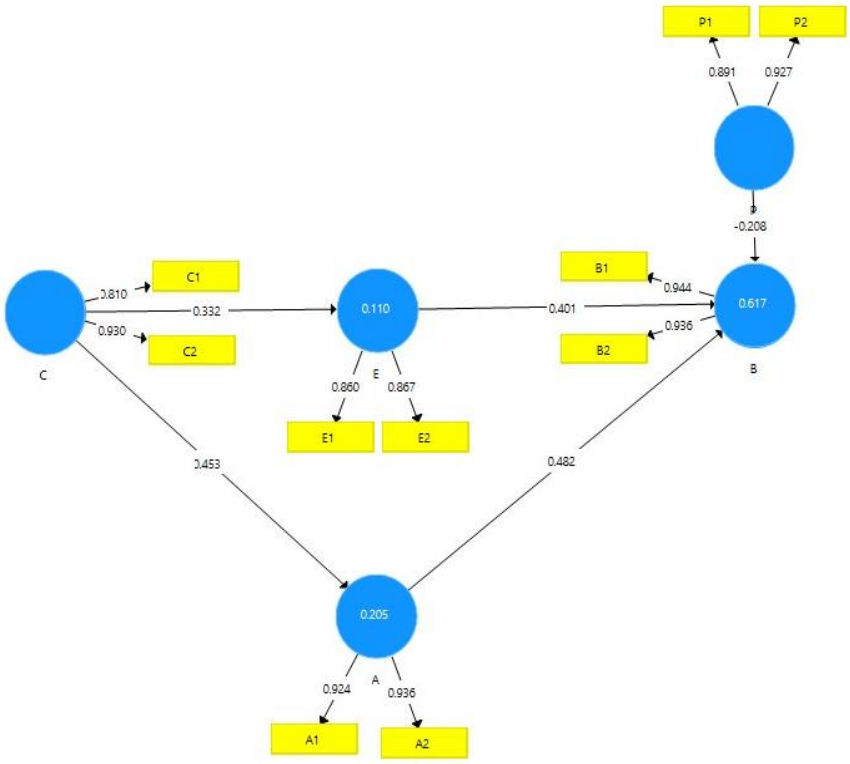


Figure 4: Final SEM model.

4 CONCLUSIONS

This study examined the factors influencing the balance between career and academic pursuits among young professionals aged 24–29 using Structural Equation Modeling (SEM).

The findings indicate that career-related factors significantly influence both academic success and emotional-related factors. Furthermore, academic success and emotional factors were found to have significant effects on balanced career and academic performance. Psychological stress factors also demonstrated a statistically significant, although weaker, relationship with balanced performance.

These results suggest that achieving balance between career and academic responsibilities is shaped by a combination of performance-related factors and stress-related conditions. In particular, the interplay between career development, academic outcomes, and emotional well-being plays a critical role in sustaining this balance.

From a practical perspective, the findings imply that young professionals may benefit from strengthening both their academic competencies and emotional coping mechanisms to effectively manage dual responsibilities. Institutions and employers may also consider providing structured support systems that address both performance demands and stress-related challenges.

However, given the limited sample size, the results should be interpreted with caution. Future research may expand the sample and incorporate additional variables to further validate and refine the proposed model.

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APPENDIX

Survey Questionnaire:

1) Career Success Indicators:
   - I find my current job or career to be fulfilling and meaningful.
   - I am satisfied with the opportunities for career advancement and promotions in my organization.

2) Academic Success Indicators:
   - I believe that the curriculum is designed to enhance both subject-specific knowledge and broader skills such as critical thinking and communication.
   - I am content that the assessments (exams, projects, etc.) used in my courses effectively measure the attainment of the learning outcomes.

3) Psychological Stress Factors:
   - I often set unrealistically high standards for myself, which can lead to stress and anxiety.
   - I frequently compare myself to others in terms of appearance, achievements, or success.

4) Emotional Stress Factors:
   - I make it a priority to take care of my physical health by staying active and maintaining a balanced diet.
   - I have a strong support network of friends and family members with whom I can openly communicate and seek guidance.

5) Balanced Career and Academic Performance Indicators:
   - I am generally resilient in the face of stress and can effectively cope with academic and career-related pressures.
   - I have a structured daily or weekly routine that helps me manage my academic and career responsibilities effectively.

AI in Education: Revolutionizing Learning and Personalized Instruction

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Keywords: Automation in Education, Artificial Intelligence (AI), Educational Technology, Administrative Tasks, Personalized Learning, Teacher Support, Smart Classrooms, Data Privacy, Collaboration, Future of Education.

Abstract: Artificial Intelligence (AI) is quickly reshaping industries globally, and the field of education is particularly poised for transformative innovation. Conventional instructional approaches frequently find it difficult to meet the varied needs and speeds of students, often resulting in deficiencies in both understanding and involvement. In response to these shortcomings, technology leveraging AI has been deployed to enrich educational experiences and boost learning achievements. The purpose of this research is to investigate how AI is fundamentally changing education, specifically concentrating on customized learning, smart tutoring systems, and improved efficiency in administrative tasks. The study adopted a literature review approach, analyzing current academic studies, case analyses, and AI implementations across both compulsory (K-12) and post-secondary education sectors. The results show that AI substantially raises student performance by providing customized teaching, adaptive evaluations, and immediate feedback via Intelligent Tutoring Systems (ITS). Furthermore, predictive data analysis enables instructors to proactively identify vulnerable students, while automation solutions alleviate administrative pressures, including tracking attendance and grading. AI-driven accessibility and language translation tools also promote an inclusive environment by assisting students from varied linguistic and cultural origins. Ultimately, AI exhibits considerable promise for enhancing individualized teaching, boosting educational effectiveness, and broadening access to high-quality learning. Nevertheless, critical issues like ethical dilemmas, data security, and the potential for decreased human interaction in educational settings require careful consideration. In summary, AI is a powerful resource that can supplement existing teaching methods, guiding the development of an educational system that is more adaptive, accessible, and successful.

1 INTRODUCTION

1.1 Background and State of the Art

The swift progression of Artificial Intelligence (AI) has significantly impacted numerous sectors, with the field of education proving to be one of the most ripe for transformation [1], [2]. Incorporating AI technologies – such as machine learning, algorithms for adaptation, natural language processing, and predictive analytics – has fundamentally changed the methods by which knowledge is conveyed, absorbed, and evaluated [3], [4]. As educators globally aim to address the complex requirements of contemporary students, AI offers a solution to the limitations of standardized, universal instruction by facilitating dynamic, data-informed, and highly tailored learning environments [5], [6]. Within conventional classroom settings, instructors struggle to accommodate the varying aptitudes, interests, and learning preferences of all students simultaneously [7]. This difficulty often contributes to inconsistencies in student achievement, engagement, and understanding.

AI-powered tools – specifically automated assessment systems, adaptive learning platforms, and Intelligent Tutoring Systems (ITS) – are designed to overcome this issue by modifying both teaching methods and content in real-time to align with each student's specific requirements [8], [9], [10]. By analyzing data instantaneously, AI can detect trends in student behavior, forecast future performance, and deliver customized feedback that improves both retention and learning results [11], [12]. Furthermore, AI assists teachers by automating routine administrative responsibilities, such as managing attendance, grading assignments, and analyzing performance metrics [13], [14]. This benefit not only saves time but also frees up teachers to dedicate more attention to student mentoring, creativity, and direct interaction [15].

In university settings, AI applications are increasingly being embedded into Learning Management Systems (LMS) to provide customized course suggestions, detect plagiarism, and automatically generate feedback [16], [17]. The rapid shift to online and hybrid education following the COVID-19 pandemic [18], [3] has amplified the need for these capabilities, underscoring the necessity for scalable and responsive educational systems. AI is also vital for boosting educational access and inclusivity. Technologies like text-to-speech, speech recognition, and automated translation enable students with language barriers or disabilities to participate more effectively in learning activities [19], [20]. Early identification and proactive, tailored support for students at risk is made possible through predictive analytics [21]. These innovations are consistent with the worldwide push for equitable education, as set out in the United Nations Sustainable Development Goal 4 (SDG 4), which seeks to ensure universal access to quality and inclusive education [18].

Despite these hopeful advancements, introducing AI into education is not without its difficulties. Concerns remain regarding ethical usage, data privacy, algorithmic bias, accountability, and the preparedness of educators [4], [2], [12]. A potential hazard is that excessive reliance on automated systems could diminish crucial human interaction and empathy within the learning environment [15]. Moreover, existing differences in digital infrastructure between regions could exacerbate the educational disparity between well-resourced and technologically advanced institutions and those with limited resources [6], [17]. Consequently, a balanced strategy is essential – one that marries the computational capability of AI with expert human pedagogical judgment to deliver educational experiences that are meaningful, ethical, and learner-centric [1], [4]. This paper investigates the pivotal role of AI in education, highlighting its potential to transform both instruction and personalized learning. Specifically, the discussion covers the structure and operation of ITS, methods for representing knowledge and domain expertise, the advantages and drawbacks of AI-powered learning, and the automation of processes for administration. By conducting a critical review of recent theoretical and empirical studies, this work intends to clarify how AI can be utilized to improve both teacher effectiveness and student engagement while simultaneously tackling the practical and ethical hurdles of its integration into modern schooling [5], [13].

1.2 Research Gap and Questions

Despite the rapid increase in studies concerning AI's role in education, there is still a significant need for a comprehensive synthesis that clearly defines the precise teaching and learning mechanisms that yield better student results, alongside offering practical and ethical guidance for implementation. Current literature frequently focuses exclusively on the technological capacity of AI or engages in abstract discussions about ethics. This paper attempts to address this deficiency by systematically examining AI's application across three core areas – Intelligent Tutoring Systems (ITS), customized instruction, and administrative automation – and presenting tangible examples of existing systems along with their related ethical challenges.

Therefore, this article seeks to answer the following research questions:

1) What distinguishes AI-driven personalized learning methods from Intelligent Tutoring Systems (ITS), and what concrete evidence is available regarding their influence on student achievement and engagement levels?
2) Which administrative functions are principally being automated by AI in educational environments, and how does this automation impact the efficiency of institutions and the changing roles of educators?
3) What are the major ethical, pedagogical, and operational challenges linked to the widespread adoption of AI in education, and what mitigating strategies are proposed based on established international ethical guidelines?

2 THE ROLE OF AI IN EDUCATION

2.1 Overview of AI

AI is a branch of computer science dedicated to developing intelligent machines capable of performing tasks typically requiring human intellect. Key subsets of AI include machine learning (ML), natural language processing (NLP), expert systems, and computer vision. These technologies allow computers to simulate human intelligence through processes like pattern recognition, data analysis, human-like interaction, and decision-making. Formally, AI involves computational systems modeling human cognitive functions such as reasoning, learning, and problem-solving [22], [2]. Historically evolving from systems based on explicit rules, the concept, which originated in cognitive psychology and computer science, has advanced to modern deep neural networks and machine learning models that facilitate independent decision-making [13], [14].

Within the educational sphere, AI is broadly understood as using computational intelligence to bolster administrative functions, learning processes, and teaching [3], [4]. Current AI systems rely on several primary subfields: NLP, ML, robotics, computer vision, and expert systems [6], [8]. ML allows systems to analyze data patterns and continuously improve performance without being explicitly programmed [5]. Through text and speech comprehension, NLP enables smoother human-computer interaction, evident in educational virtual assistants and chatbots [19]. Computer vision enables features like automated remote proctoring, gesture recognition, and accessibility tools for disabled students [20]. Expert systems replicate the logic of human experts, while robotics provides opportunities for hands-on, practical experiences, especially in science, technology, engineering, and mathematics (STEM) fields [21].

The proliferation of Big Data, combined with enhanced computing power, has significantly sped up the adoption and development of AI in educational contexts [1], [11]. Intelligent Tutoring Systems (ITS), adaptive learning environments, and Learning Management Systems (LMS) now leverage real-time data analysis to optimize teaching strategies and customize content [12], [10]. For example, AI algorithms can track student interactions, predict their future learning path, and suggest specific resources to address knowledge gaps [4], [17]. These advancements are part of the larger movement toward data-driven education, where instructional decisions are constantly refined using evidence from digital feedback loops [16].

The influence of AI also increasingly covers institutional management and educational administration. Systems for automated resource allocation, enrollment prediction, and grading enhance operational effectiveness and decrease the workload on staff [15], [13]. Furthermore, AI-powered analytical tools assist educators and policymakers in evaluating institutional performance and curriculum effectiveness [2], [14]. By merging natural language comprehension and predictive analytics, institutions can implement early warning systems to identify and proactively support students facing academic difficulty [6], [12]. Despite these promising uses, AI remains a multifaceted, cross-disciplinary domain that integrates cognitive science, educational psychology, data analytics, and computer science [1]. Its effective deployment necessitates not only technological infrastructure but also a foundational understanding of pedagogy and ethical principles to ensure AI serves as a complement to, rather than a replacement for, human instruction [4], [8]. Consequently, educators and researchers must grasp the fundamental workings and mechanisms of AI to utilize its potential effectively and ethically in the pursuit of fair and personalized learning.

2.2 AI Applications in Education

AI has found diverse applications in education, altering traditional teaching models and opening up new possibilities for customized training and adaptive instruction. The following subsections outline key areas where AI is making a substantial impact on education.

2.2.1 Personalized Learning

The capacity of AI to deliver learning experiences tailored to the individual is one of its most compelling advantages in education. AI-driven systems are able to collect and process vast amounts of student data, including academic progress, performance metrics, preferred learning methods, and individual learning styles. Algorithms then leverage this information to customize educational materials, learning activities, and assessments to match the specific needs of each learner. By focusing on areas needing more attention and presenting suitable challenges to encourage continuous progress and engagement, personalized learning ensures that students advance through their education at a suitable pace.

2.2.2 Adaptive Learning Technologies

AI-enabled adaptive learning platforms have fundamentally revolutionized the classroom experience. These platforms continuously analyze and assess student responses, behavioral data, and performance results using machine learning algorithms. To optimize the learning process, adaptive platforms dynamically adjust the lesson content, difficulty level, and instructional speed, providing focused feedback, advanced challenges, and remedial resources. This adaptive methodology guarantees that every student receives individualized instruction by addressing their unique learning strengths and deficiencies.

2.2.3 Intelligent Tutoring Systems (ITS)

ITS are advanced AI platforms designed to replicate the individualized attention a human tutor provides. They use AI to interact with students, evaluate their comprehension, offer instructional guidance, and deliver corrective feedback to foster deep subject mastery and active participation. In contrast to more general adaptive systems, ITS typically incorporate a detailed domain model (representing expert knowledge) and a student model (reflecting the learner's current knowledge state) to inform pedagogical decisions, making them highly effective for mastering complex topics [8], [21].

2.2.4 Automated Administrative Tasks

AI technologies are also critical in automating a variety of administrative functions in educational settings. Grading stands out as a key area where AI has brought major advancements. Automated systems utilize machine learning to grade examinations, assignments, and quizzes, which drastically cuts down on the manual time required from educators. Furthermore, AI-powered analytical tools examine student data to pinpoint patterns, trends, and areas needing improvement, thereby empowering educators to make evidence-based decisions. By streamlining these administrative duties, AI provides teachers with more time to concentrate on instructional activities, personalized mentorship, and direct student engagement.

2.3 Benefits of AI in Education

The integration of AI into education has yielded substantial and transformative benefits across administration, learning, and teaching. Utilizing adaptive algorithms, data analytics, and computational intelligence, AI improves instructional personalization, efficiency, inclusivity, and decision-making capabilities [1], [4]. Beyond enhancing student outcomes, these advantages contribute to a more responsive and fair learning environment.

Equity and Individualized Instruction: AI enables individualized instruction, allowing teachers to effectively accommodate the varied learning styles and unique requirements of their students. By adjusting the pace and content, AI ensures optimal learning for every student.

Increased Engagement: AI fosters student motivation and participation through engaging and immersive educational experiences. Components like ITS and gamification keep students actively invested in the learning journey.

Improved Efficiency: AI boosts the efficiency of administrative operations, lessening the burden on educators and allowing them to focus more on student support and instruction.

Evidence-Based Decision-Making: AI supports decision-making informed by data, offering valuable insights into student performance, learning trends, and specific areas for development.

3 PERSONALIZED INSTRUCTION AND ADAPTIVE LEARNING

3.1 Differentiating Personalized Instruction, Individualized Learning, and Adaptive Learning

Personalized instruction is an educational philosophy that customizes the learning experience to align with a student's unique talents, interests, and requirements. It is founded on the recognition that students possess distinct learning preferences, styles, and existing knowledge bases, and therefore aims to match instructional methods and content to what is most appropriate for each learner. This approach moves beyond generic education models by striving to establish bespoke learning paths that maximize student achievement, motivation, and engagement. Although often used interchangeably, it is important to clarify the distinctions among three key terms:

- Individualized Learning. The main focus here is on the rate of progress. Students cover the identical curriculum but at a pace that suits them.
- Personalized Instruction. This goes beyond merely regulating the pace to actively

differentiate how and what students learn, modifying learning goals, content, and pedagogy based on demonstrated competence, individual needs, and interests. It centers on progression based on mastery.

- Adaptive Learning. This represents a mechanism driven by technology that instantaneously modifies instruction in response to a student's actions and performance. It employs AI algorithms (such as Bayesian knowledge tracing) to dynamically adjust the nature and complexity of the material or questions to immediately target specific learning deficiencies [2], [10]. Essentially, adaptive learning functions as a tool that facilitates personalized instruction.

3.2 AI-Powered Techniques for Personalization

AI technologies are fundamental to implementing personalized instruction. By utilizing machine learning algorithms, AI systems can gather, analyze, and interpret large datasets concerning each student. This data encompasses information such as their progress tracking, learning preferences, performance evaluations, and other relevant metrics. AI algorithms then use this analyzed data to create tailored interventions, adaptive learning routes, and unique recommendations. The core of personalization lies in AI's capacity to model the learner's current knowledge state and make dynamic, real-time adjustments to the content flow, instructional support, and sequence of material.

Adaptive learning systems use AI to dynamically adjust content, pacing, and difficulty based on real-time student performance [2], [10]. These systems rely on machine learning models that continuously analyze learner interactions – such as quiz responses, time spent on tasks, and error patterns – to predict knowledge mastery and suggest appropriate next steps [6], [21].

Example: Bayesian Knowledge-Tracing (BKT). Platforms like ALEKS and Knewton employ BKT models to map individual learning trajectories, ensuring that each student receives instruction suited to their current skill level [11], [12]. BKT algorithms calculate the probability that a student knows a specific skill based on their history of correct/incorrect answers, and then presents problems that are optimally challenging (the "zone of proximal development").

3.3 Adaptive Learning Technologies in Practice

One of the most significant practical applications of AI in personalized instruction involves adaptive learning technologies. Adaptive learning systems use AI algorithms to continuously evaluate and track student progress, subsequently adjusting the instructional pace and content to match. These systems are capable of identifying subjects where students struggle or excel, and then providing dynamically appropriate challenges, materials, and activities. By adapting to the specific requirements of learners, adaptive technologies refine the learning experience, promoting greater mastery of the subject matter, engagement, and understanding.

3.3.1 Machine Learning Algorithms in Adaptive Learning

The foundation of adaptive learning technologies is built upon machine learning algorithms. These algorithms analyze data trends, recognize patterns, and forecast students' learning styles, strengths, and existing knowledge gaps. As students interact with the adaptive system, their performance data and responses are constantly being analyzed, enabling the system to provide real-time, personalized and adaptive instruction. Furthermore, ML algorithms can utilize aggregated data from numerous students to refine and enhance the underlying adaptive learning models.

3.3.2 Real-Time Feedback and Remedial Support

Adaptive learning systems offer instant feedback on student performance, allowing students to immediately grasp their weaknesses and strengths. This rapid feedback loop empowers students to self-assess their comprehension and modify their study approach as necessary. Additionally, adaptive learning platforms are able to deliver customized remedial support, offering targeted resources and instruction to overcome areas of particular difficulty.

3.3.3 Customized Learning Paths

Adaptive learning technologies create customized learning paths for each learner based on their individual needs and progress. Learners can navigate through the content at their own pace, receiving

additional support or advanced challenges as necessary. The learning paths can be adjusted dynamically, ensuring that learners are appropriately challenged and engaged throughout their educational journey. Customized learning paths allow learners to take ownership of their learning, fostering autonomy and self-directedness.

3.4 Influence on Learning Outcomes and Student Engagement

Adaptive learning and personalized instruction have a substantial influence on student achievement and engagement. When instruction is customized to individual preferences and needs, students are more likely to be motivated and take an active role in their learning. Adaptive learning platforms maintain consistent student engagement by delivering challenging and relevant materials. Moreover, personalized instruction fosters a deeper command of the subject matter by addressing specific knowledge gaps and building upon prior knowledge. Consequently, students see better academic performance, including greater retention, higher levels of mastery, and improved overall learning outcomes.

4 INTELLIGENT TUTORING SYSTEMS

4.1 Defining Intelligent Tutoring Systems (ITS)

ITS constitute a class of educational technology that utilizes AI to deliver personalized support, instruction, and guidance to students. Their core purpose is to simulate the high degree of effectiveness seen in one-on-one human tutoring, which is widely recognized as one of the most impactful teaching modalities. Unlike static instructional software, an ITS engages with students interactively, adapting the teaching sequence based on the learner's evolving knowledge state, correcting misconceptions, and offering immediate feedback [8], [21].

A typical ITS is composed of three interconnected modules:

- Domain Model. This module stores the foundational expert knowledge, key concepts, and problem-solving methods for the subject being taught.
- Student Model. This component monitors the student's current understanding, learning rate, progress, and areas of confusion.
- Pedagogical Model. This module determines the instructional strategy, specifically how and when to intervene, and what content to present next, by drawing insights from both the student and domain models.

4.2 Domain Expertise and Knowledge Representation in ITS

The specialized knowledge and expertise of a subject form the necessary underpinning of ITS. These systems operate using extensive knowledge bases and expert models relevant to the material being taught. These models enable the ITS to accurately assess student performance, deliver justifications, and provide relevant feedback and guidance. Foundational to any AI-driven educational platform is effective knowledge representation. This dictates how the relationships, skills, and subject matter knowledge are organized, stored, and accessed by the intelligent algorithms [22], [14]. In the realm of AI in education, domain expertise signifies the system's ability to imitate the instructional approaches and cognitive comprehension of human subject-matter experts [21], [9]. This is achieved using diverse formalisms for representation, such as Bayesian networks, semantic networks, and production rules, which allow the ITS to execute sophisticated reasoning tasks like diagnosing errors, solving problems, and generating customized learning content [10], [15].

4.2.1 Student Modeling and Assessment

Each learner's unique traits, knowledge, abilities, learning preferences, and progress are captured in a comprehensive model that ITS build. Learner interactions and performance data are used to continuously update these models. To evaluate the learner's comprehension, spot knowledge gaps, and decide on the right amount of instructional support, the system uses AI algorithms.

4.2.2 Instructional Strategies and Feedback

To enhance learning, ITS use a range of teaching techniques. They can present instructional content through multimedia resources, interactive activities, and virtual simulations. Learners receive real-time feedback from the system, which fixes mistakes, rewards accurate answers, and provides clarifications when necessary. A deeper comprehension of the material is encouraged by the feedback, which is customised and suited to each learner's unique needs.

4.2.3 Adaptive Instruction and Scaffolding

ITS capacity to modify instruction to meet each student's unique needs is one of their main advantages. The system offers advanced challenges for proficient learners, offers extra practice or remedial resources for difficult concepts, and dynamically modifies the tasks' level of difficulty. By ensuring that students are suitably challenged and assisted, this adaptive approach fosters ongoing development and mastery.

4.3 Limitations and Advantages of ITS

The adoption of ITS in education has shown significant promise for improving learning and teaching outcomes across numerous subjects. By integrating cognitive science, AI, and data analytics, ITS deliver personalized learning experiences that adapt to individual student requirements, promoting deep understanding and continuous engagement [21], [14], [15].

- Customized Support and Instruction. ITS, leveraging AI, provide individualized support and teaching based on the distinct requirements of each learner. The system modifies itself based on the student's unique learning preferences, progress, and knowledge gaps, ensuring that instruction is delivered at an appropriate pace. This bespoke strategy enhances motivation, engagement, and learning outcomes.
- Individualized Assessment and Feedback. ITS offer immediate, highly targeted feedback on performance, a crucial element often absent in conventional classrooms. This rapid, error-specific feedback facilitates instant correction and more effective learning for students. Furthermore, ITS enable ongoing, non-disruptive assessment, replacing traditional high-stakes testing with formative evaluation that continuously guides the learning process.

However, integrating ITS also faces several hurdles:

- High Development Costs and Required Expertise. Creating a comprehensive and effective ITS demands significant time, substantial development effort, and profound domain expertise. The considerable initial investment in funding, time, and specialized knowledge can hinder widespread implementation.
- Transferability and Scalability. An ITS designed for one domain may not be easily or successfully applied to another. ITS often have a high degree of domain specificity, which restricts their general applicability and transferability across different educational contexts and subjects.
- Emotional and Social Factors. ITS frequently prioritize cognitive aspects of learning, often neglecting the emotional and social dimensions. While they offer customized instruction, ITS cannot fully replicate the emotional support and social interactions provided by human educators.
- Ethical Concerns. The use of AI in education, including ITS, raises numerous ethical questions. Privacy and security for student data must be rigorously protected. To prevent unfair discrimination or bias, the underlying AI algorithms must be transparent and understandable.
- Risk of Over-Reliance. A notable pedagogical concern is the potential for excessive dependence on technology. Over-automation may reduce human connection and emotional involvement, both essential for cultivating critical thinking skills and motivation [17], [16].

5 AUTOMATION OF ADMINISTRATIVE TASKS IN EDUCATION

5.1 Overview of Administrative Automation

AI-powered automation is becoming increasingly central to optimizing the administrative and operational duties of educational organizations. Beyond direct classroom teaching, AI is now being integrated into the educational sphere to automate essential administrative functions that are critical for efficient institutional operation. By automating repetitive and time-intensive administrative tasks, institutions empower staff and teachers to dedicate more energy to strategic, student-focused, and pedagogical activities [14], [2]. Through the use of intelligent algorithms, natural language processing (NLP), and machine learning, institutions can manage routine operations with greater accuracy, efficiency, and financial prudence [21].

5.2 Key Areas of Administrative Automation

AI is currently being employed to automate a wide spectrum of administrative duties across higher education, secondary, and primary levels:

5.2.1 Registration and Student Enrollment

The processes of student registration and enrollment can be streamlined through automation, improving the management and collection of student data. Automated online registration forms, document uploads, and data entry systems substantially lessen the manual effort required by administrative personnel. Moreover, automation facilitates real-time data validation, which ensures that student records are accurate and current, thereby supporting improved resource allocation and planning.

5.2.2 Automated Feedback Generation and Grading

AI tools are increasingly used for the automated grading of various assessments, particularly essay questions, short answers, and multiple-choice tests [16], [17]. Systems use NLP and machine learning algorithms to accurately evaluate student responses against predefined assessment standards. AI is also capable of going beyond simple score assignment to generate tailored, constructive feedback on student submissions, which saves instructional time and accelerates the student learning cycle [23].

5.2.3 Monitoring and Attendance Tracking

AI is enabling a shift from traditional manual attendance procedures to automated monitoring systems. AI platforms can automatically log and track student presence by integrating with LMS log-in data, utilizing Wi-Fi tracking in classrooms, or employing facial recognition technology. This not only enhances the precision of attendance records but also provides instant data that can be used to promptly identify and address problems related to absenteeism.

5.2.4 Resource Management and Scheduling

Optimization algorithms rooted in AI can generate highly efficient academic schedules, considering factors like pedagogical needs, classroom availability, teacher workload, and student enrollment. Automated scheduling minimizes scheduling conflicts and optimizes the utilization of resources (e.g., equipment, lab facilities), thus reducing the time administrative staff spend on manual adjustments and rescheduling.

5.2.5 Data Analysis and Report Generation

The automation of generating various reports – including student progress summaries, attendance reports, and financial statements – is possible to save time and ensure data accuracy. AI-driven data analytics tools can analyze institutional data to predict future needs (e.g., budget, enrollment), identify emerging trends, and support strategic decision-making by institutional leaders [14], [2].

5.3 Advantages of Automating Administrative Tasks

The application of AI to automate administrative processes represents a major development in modern education management. By employing predictive analytics, NLP, and machine learning, educational institutions can streamline their operations, boost productivity, and improve service delivery [14], [2].. Automating these tasks also reduces human error and workload, freeing up time for both teachers and administrators to focus on high-quality instruction, strategic planning, and deeper student engagement [15], [21].

- Resource and Time Savings. Automation of administrative duties allows administrators and educators to conserve a significant amount of time. By spending less time on manual labor, they can concentrate on high-priority activities such as instructional planning, curriculum development, and student support.
- Consistency and Accuracy. Automated systems process data with high levels of precision, which drastically minimizes the human errors commonly linked with manual grading, data entry, and record-keeping. This ultimately enhances the consistency and trustworthiness of institutional data.
- Support for Strategic Decisions. AI-driven data analysis and reporting offer timely, reliable insights into resource utilization and institutional performance for school leaders. This facilitates evidence-based and more informed strategic planning.

5.4 Ethical Considerations and Challenges in Administrative Automation

While administrative task automation offers many advantages, it also presents complex practical and ethical concerns [25]:

- Security and Data Privacy. The process relies on gathering and processing sensitive information about staff and students, making strict compliance with data privacy regulations (e.g., FERPA, GDPR) and robust cybersecurity measures absolutely mandatory.
- Algorithmic Bias. When algorithms used for predictive modeling, admissions, or resource allocation are trained on historical data that exhibits bias, they risk reinforcing or even amplifying systemic prejudices against certain demographic groups.
- Accountability and Transparency. The lack of transparency, sometimes called the "black box" problem, associated with specific AI algorithms makes it challenging to explain the reasoning behind automated decisions, which is a major ethical issue when these decisions involve high-stakes outcomes like resource distribution or a student's academic status.
- Job Displacement and Change Management. Implementing automation necessitates substantial investment in staff training and infrastructure. A legitimate concern exists that automating administrative tasks could result in job losses for support staff, necessitating proactive strategies for staff retraining and role reassignment.

5.5 Mitigation Strategies

To ensure that administrative automation is deployed both effectively and ethically, institutions should follow these guidelines:

- Maintain Human Oversight. Decisions deemed critical, especially those with significant personal consequences, must always be subject to human review and supervision, with AI serving purely as a tool for recommendation.
- Conduct Bias Audits and Ensure Fairness. Automated systems must be regularly tested and audited for algorithmic bias across all demographic lines to guarantee equitable results.
- Enforce Strict Data Governance. Implement clear policies for data governance and robust measures for data security that comply with all pertinent privacy laws.
- Focus on Augmentation, Not Substitution. Automation of administration should be viewed as a tool to enhance staff capabilities and free up time for high-value human tasks, rather than a method for reducing staff numbers to cut costs.

6 CONCLUSIONS

The way educational institutions run could be completely changed by automating administrative duties, giving administrators and teachers more time and resources to devote to more worthwhile endeavours. Administrative procedures like scheduling, grading, student enrolment, attendance tracking, and report generation can be made more efficient, accurate, and data-managed by utilising technology and AI.

AI also offers powerful tools for revolutionizing the core of education: teaching and learning. Through ITS and adaptive learning technologies, AI enables true personalization by dynamically adjusting content and pacing to meet the unique needs and knowledge state of every student, leading to higher mastery and engagement [21].

The implementation of automation and AI in education presents certain challenges, including infrastructure constraints, equity concerns, data privacy issues, and resistance to change. However, these challenges can be addressed with careful planning, ethical considerations, and training. It is essential to make sure that automation is applied in a way that respects privacy, is inclusive, and does not reinforce prejudices or discriminate against particular people or groups.

Educational institutions can establish a more productive and efficient administrative environment by embracing automation in the classroom, which will ultimately benefit students, teachers, and the educational community as a whole. While administrators can strategically manage their time and resources, educators can concentrate on their primary duties of teaching, curriculum development, and student support thanks to automation. In order to establish a learner-centred educational ecosystem, it is critical to modify automation strategies and remain proactive in seizing new opportunities as technology develops.

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SECTION 4

CONTROL AND AUTOMATION

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Efficient Production Management System with a Packaging Quality Control Module

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Keywords: KPI, Automation, Defect Recognition, Machine Learning, Convolutional Neural Network, Packaging.

Abstract: The paper presents a comprehensive study aimed at improving the efficiency of the mayonnaise manufacturing and packaging process by analyzing the key performance indicators of the mayonnaise making machine, developing the structure of a packaging quality recognition system, and modeling a convolutional neural network to identify packaging defects. The article analyzes key performance indicators for productivity, energy efficiency, product quality and equipment downtime. A system has been developed for recognizing the quality of packaging, which is part of the indicator of the level of product defects, based on the use of modern machine vision algorithms. The final part of the study presents the results of modeling and training a convolutional neural network for automatic detection of packaging defects. Experimental results demonstrate a high level of accuracy and reliability of the proposed system, which makes it possible not only to timely identify defective products, but also problems in the operation of the machine in the early stages of its operation. This in turn helps reduce waste, improve production process efficiency and reduce maintenance costs.

1 INTRODUCTION

Improving the efficiency and quality of production processes is a key challenge for the modern food industry. The production of mayonnaise as one of the popular food products requires special attention to quality control at all stages of the production cycle. One of the most important components of this process is the analysis of key performance indicators (KPIs) [1], [2] of production equipment, which allows timely identification of problems and optimization of machine operation.

In addition to control over the production process, the quality of the final product, in particular its packaging, is also important. Packaging defects can lead to significant losses for both the manufacturer and the consumer. Incorrect or damaged packaging not only detracts from the appearance of the product, but can cause mayonnaise to spoil due to the penetration of air or bacteria. This leads to a reduction in expiration date, possible complaints from consumers and additional costs for processing or disposal of defective products [3]. Therefore, the development of an effective system for recognizing packaging defects is a necessary condition for ensuring high quality standards [4]-[6].

In this context, machine learning and modern image processing techniques play an important role in automating quality control processes. Convolutional neural networks (CNNs) have proven to be a powerful tool for pattern recognition and can be effectively used to identify defects in product packaging [7], [8]. However, confidence is required regarding the capture of individual defects characteristic of the process being studied. Such defects, in addition to the typical obvious tears, damage and missing parts of the packaging, also include the absence of a manufacturing date and a significant printing defect. Using CNN in combination with KPI analysis opens up new

opportunities for automating quality control and increasing production efficiency.

The goal of this research is to create an integrated system that combines analysis of mayonnaise machine KPIs, system structure for packaging quality recognition, and CNN modeling for defect detection. The combination of these aspects will not only improve the quality of the final product, but also ensure timely identification and elimination of problems in the operation of production equipment.

2 LITERATURE REVIEW

Performance measurement and management methodology (PMM) provides management with many critical, useful and necessary functions and consists of three stages: performance planning, performance improvement and performance analysis [9]. Equipment KPIs are typically used to identify problems related to equipment performance. These include: low productivity, frequent breakdowns, high maintenance costs. Careful analysis and monitoring of key performance characteristics allows tracking changes in equipment performance and reliability [10], [11]; make informed, timely decisions to relevant specialists regarding drawing up plans for various types of repair work, modernization or replacement of equipment; optimize costs for equipment maintenance and repair, improve product quality[12]. KPIs must be measurable, achievable, relevant and timely.

KPIs are also tools for management, decision support and forecasting [13]. Accurate performance forecasting allows you to refocus decisions to optimize performance while reducing cost and effort. For this purpose, various methods of artificial intelligence [14], machine learning [15]-[17], etc. have been actively used recently.

In the production of mayonnaise, packaging defects can affect the quality of the product, its shelf life and demand. The main types of packaging defects include deformation, problems with the lid, printing defects on the packaging, and mismatched labels.

The article uses two main methods to achieve the research goal: analysis of key performance indicators (KPIs) of production equipment, development of a system for recognizing packaging quality, and CNN modeling for identifying packaging defects.

3 METHODS

Considering [1], [2], it can be argued that KPIs of equipment for the production of mayonnaise are a set of indicators used to quantify the performance and reliability of the equipment. For sauce production equipment, the following KPIs can be distinguished (Fig. 1): productivity (the amount of sauce that can be produced by the equipment per hour, day or week), downtime (the time during which the equipment does not work due to breakdown or maintenance), maintenance costs (the total cost of all types of expenses associated with equipment maintenance), uptime (operation time (may be an average indicator) of equipment without breakdowns), product quality (sauce quality), energy efficiency (the amount of energy resources used by the equipment during mayonnaise production), resource efficiency (amount of resources (except energy) used by the equipment in the production of sauce), defect rate (proportion of products that do not meet standards from the total production volume), packaging deficiency (percentage of sauce packs that do not meet quality standards and must be removed from the line.

Cloud platforms provide centralized data storage, processing and visualization, which helps identify trends, predict failures and optimize production processes. Visualization of key performance indicators is carried out using dashboards that provide clear graphs, charts and other visual elements for monitoring that meet quality standards), uptime (measured as total uptime without failures), resource efficiency (use of ingredients and energy), failure and downtime rates, and identification of packaging shortages.

To effectively use KPIs, it is necessary to improve the data collection and analysis system, which is integrated into the production process and includes industrial Internet of Things (IoT) architecture. Integration of other KPIs into the cloud is carried out through field buses of the machine control system and IoT gateway (for example, Raspberry Pi). The IoT gateway acts as a central node that collects data from various sensors and devices (Fig. 2 also shows exchange protocols), including cameras that monitor the quality of packaging. The IoT gateway processes data on site and transfers it to the cloud for further analysis and storage of production processes in real time. As a dataflow development platform, Node-RED is the ideal tool for creating such dashboards.

Dashboards created in Node-RED can be accessed through web interfaces or specialized applications on phones and tablets, allowing you to quickly respond to changes and make informed decisions. This makes production management more flexible and efficient, helping to improve overall productivity, reduce costs and ensure high product quality.

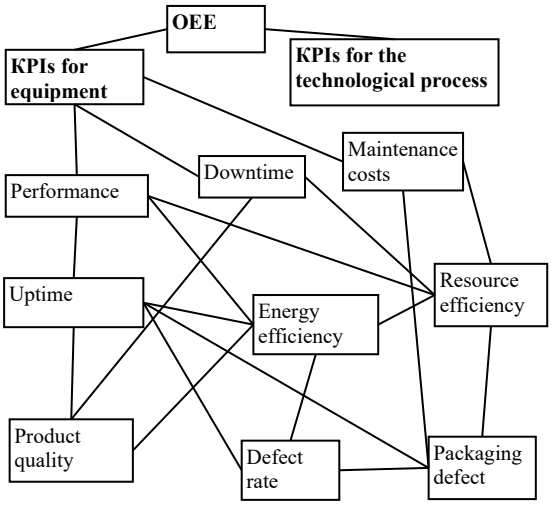


Figure 1: KPIs connection diagram for mayonnaise production.

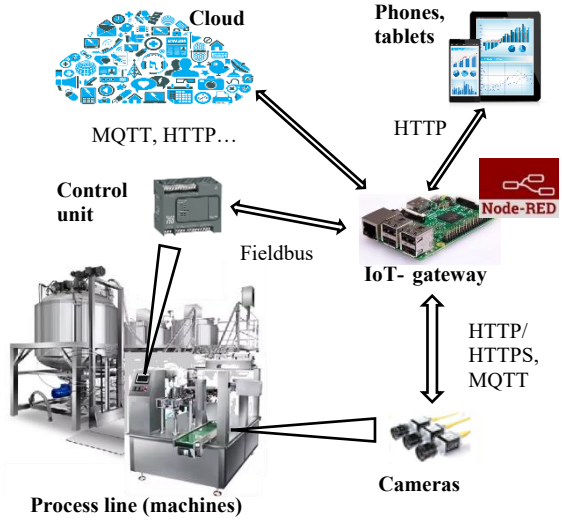


Figure 2: Automated control system with integration.

CNN modeling for mayonnaise packaging defect detection involves data collection and annotation, image pre-processing, model building and training, and model performance evaluation. The images are captured using high quality cameras installed on the production line. To ensure data diversity, images are collected from different angles, under different lighting conditions and with different types of defects implemented (simulated) by the developer. To quickly implement the system, several training samples were collected and a decision was made to use pre-trained models. The images are manually annotated to label defects (Fig. 3).

Transfer learning [18] is a popular deep learning method that uses already trained models for new tasks. This approach offers significant benefits, making training faster, more accurate and cost-effective. Pre-trained models have knowledge of basic features and patterns, saving time and resources that would otherwise be spent on training from scratch. This leads to better results, especially when the data set for a new problem is small or limited. Transfer learning helps avoid overfitting and saves computing resources. However, transfer learning also has disadvantages. Models may not be flexible for specific tasks, and retraining may require significant resources. There are also architectural limitations, risk of overfitting, licensing restrictions, influence of biases and knowledge limitations. Therefore, it is recommended to use transfer learning as a quick start, and then, after collecting a representative sample of typical defects, retrain the model from scratch for better adaptation to the task.



Figure 3: Examples of a dataset for recognizing packaging defects.

Before using the image to train the model, pre-processing is carried out, including: normalization, reducing pixel resolution to reduce computational complexity to 620x288, data augmentation (rotation, horizontal and vertical display, changing brightness and contrast) to increase data diversity.

The model architecture includes the following layers:

- base model without an upper classification layer, which allows you to save all pre-trained features.
- Global Average Pooling 2D to reduce spatial dimensions and obtain one value for each channel.
- Dense layer – a fully connected layer with 1024 or 512 neurons for additional training on a new data set.
- Dropout layer to reduce overtraining by randomly disconnecting neurons during training, values of 0.05 and 0.2 were used.
- the original layer with the softmax function for classifying the presence of defects.

To train the model, we used the binary cross-entropy loss function and the Adam optimizer. The batch size is the entire set, the number of epochs is 20. To evaluate the performance of the model – the proportion of correctly classified images, taking into account that the number of defective and normal samples is the same, the Accuracy metric was used.

4 SIMULATION RESULTS

Python and R programming languages were used to develop the CNN model for rapid implementation. Python was used to develop and train the CNN model using libraries such as TensorFlow or PyTorch. R, known for its statistical and visualization capabilities, is used for data preprocessing and analysis of results.

Table 1 shows the results of training the specified network with different hyperparameters. Apparently, the accuracy on the test set for the last two architectures is 1.00, that is, the model achieved an ideal result, classifying all images without errors. This indicates the model's strong ability to recognize packaging defects, although further testing on more diverse data sets may be required to confirm the generalization ability of the model.

Table 1: Training results.

Architecture for CNN	Loss		Accuracy	
	Training set	Test set	Training set	Test set
1. n_dense=1024, dropautrate=0.05	0.31	0.93	0.65	0.50
2. n_dense=1024, dropautrate=0.2	0.34	0.91	0.32	1.00
3. n_dense=512, dropautrate=0.2	0.37	0.89	0.34	1.00

For test samples p_i, (where i=1,2,3 is the network architecture), a detailed determination of the probability of the presence of non-defective packages is presented. Figure 4 shows four samples from the test set.

The probability for the first architecture on all samples is less than the threshold (threshold =0.5), that is, even good samples are classified as bad – here the model is clearly overtrained. The second and third architectures have different p_i values. Considering that when the model is functioning, it is unacceptable for defective products to reach the manufacturer, the second architecture was finally chosen. This choice was also confirmed by considering Learning curves (Fig. 5).

The implementation of the developed CNN model in Node-RED can be done through special nodes that allow to run Python code. In addition, there are nodes that allow to run R scripts, which integrates statistical analysis directly into the data stream. This combination of Python and R provides a flexible and powerful system for automatically detecting packaging defects, which improves the efficiency of the developed model.

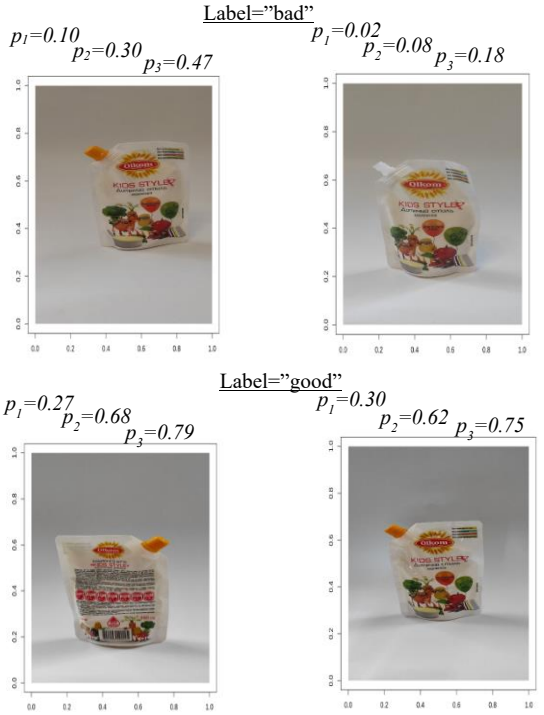


Figure 4: Test results.

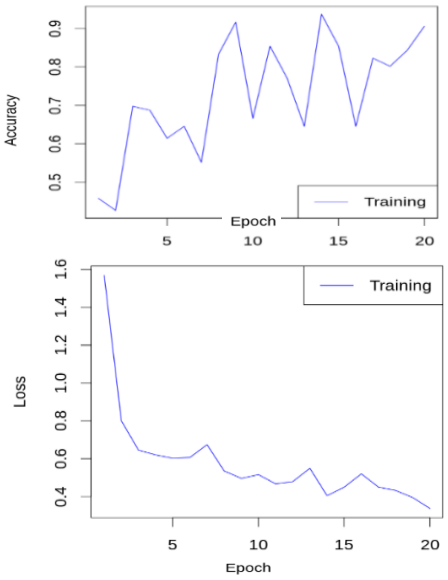


Figure 5: Learning curves on the training sample.

5 CONCLUSIONS

An integrated system for efficient mayonnaise production management, including a packaging quality control module, was successfully developed.

1) The IoT-based KPI monitoring system provides automated real-time data collection and visualization, enabling the timely tracking of productivity, downtime, and defect rates to optimize equipment operation.
2) The packaging defect recognition subsystem was implemented using a CNN model with the Transfer Learning approach.Experimental results demonstrate high accuracy: two CNN architectures achieved an accuracy of 1.00 on the test set. Based on learning curve analysis and reliability requirements, an architecture was selected to minimize the passing of defective products.
3) The proposed integrated system significantly reduces the number of defective products, improves the overall efficiency of the production process (OEE), and lowers the costs associated with error correction and maintenance.

Future work will focus on gathering a more representative defect sample to retrain the model from scratch, thereby improving its generalization ability.

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Robust Indoor Mapping on a Smart Walking Aid via Visual SLAM

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Keywords: Visual SLAM, RTAB-Map, Indoor Mapping, Smart Walking Aid, Assistive Technology, Edge Computing.

Abstract: The underlying research project aims to enhance independent mobility for elderly users by enabling indoor navigation assistance in a smart walking aid. A robust mapping system is crucial for such a device to ensure safety, effectively avoid obstacles, and create an optimal navigation path for users. Current approaches often rely on expensive sensors (e.g. LIDAR) or suffer from drift in unstructured environments. This paper proposes an optimized Visual SLAM solution based on the RTAB-Map framework for indoor mapping with a walking aid-mounted RGB-D camera. The method leverages appearance-based loop closure detection and parameter optimization to reliably generate both 2D occupancy grids and 3D point clouds under challenging conditions, like rooms located on different levels and transitions between rooms that are difficult to detect due to their layout. Indoor experiments demonstrate that the optimized system successfully handles typical walking aid motions and indoor scene features, achieving accurate reconstruction of corridors and rooms. Mapping accuracy is validated against the floor plan, showing lower drift than the baseline Visual SLAM setup. The results indicate that RTAB-Map, with proper parameter tuning, provides a solid and cost-effective mapping solution for assistive walking aid platforms, facilitating safe navigation support for the elderly.

1 INTRODUCTION

By the middle of the 2030s, the number of people in Germany at retirement age is expected to increase by approximately 4 million to at least 20 million, as seen on Figure 1. The number of individuals aged 80 or over will remain stable initially, but is expected to rise significantly after the mid-2030s [1], likely leading to a higher demand for long-term care. These demographic changes pose challenges for society that are already visible in today's age structure.

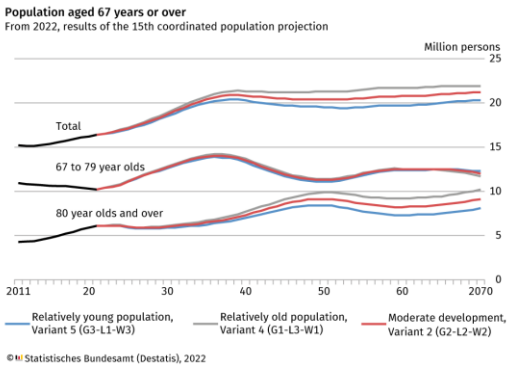


Figure 1: German population projection [1].

To address this trend, the AktiMuW[1] project [2] was initiated to provide an ageing population with a degree of autonomy by integrating technical solutions into a conventional walking aid. In addition to key functions such as sensor fusion-based analysis of body posture [3] and machine learning-based detection of potentially hazardous objects to respond to the high risk of injuries and mortality in road traffic accidents that pedestrians face with increasing age [4], another goal is to assist users in navigating indoor spaces (e.g., living environments, care facilities), which motivates integrating a Visual SLAM (Simultaneous Localization and Mapping using cameras) system on the walking aid. Visual SLAM [5] enables a device to map unknown environments and localize itself without GPS. RGB-D and stereo cameras provide both visual and depth, making them well-suited for robust indoor SLAM tasks. Combining with robotic interaction and reinforcement learning enables to handle objects [6].

This work investigates the use of RTAB-Map (Real-Time Appearance-Based Mapping) [7] on a walking aid-mounted stereo camera and an embedded GPU board. RTAB-Map is an open-source Visual SLAM framework that incrementally builds 3D maps

[1] https://www.hs-anhalt.de/aktimuw/uebersicht.html

with appearance-based loop closure. It is ROS2-compatible (Robot Operating System 2) [8] and can run on resource-limited hardware.

Few studies explicitly explore vision-based SLAM on walker-like aids. Notably, Panteleris and Argyros developed the c-Walker – a rollator platform equipped with an RGB-D (Kinect) camera – and implemented a Visual SLAM system that simultaneously tracks moving objects and builds a 3D map of the static environment. They report real-time mapping on the walker with low-end CPUs [9]. Feltner et al. also describe a Kinect-based rollator for the visually impaired, pointing out that a Kinect and Visual SLAM approach is promising for the c-Walker [10]. In summary, the only published SLAM work on rollator-style devices we found involves specialized walkers with RGB-D cameras (e.g. the c-Walker). To our knowledge, no prior work has run modern feature-based SLAM (RTAB-Map, ORB-SLAM3, etc.) on a standard push-style rollator. Thus, applying an up-to-date visual SLAM framework on a commodity walker as a modular system remains novel.The main contribution integrates a ZED Mini stereo camera and Jetson Orin Nano into a ROS2-based SLAM pipeline; correcting TF transforms for consistent spatial frames; optimizing SLAM parameters (e.g., switching from GTFF/ORB (Good Features To Track / Oriented FAST and Rotated BRIEF) [11] to KAZE (jap. wind) [12] feature descriptor); and demonstrating stable 2D/3D mapping results in real indoor environments.

2 COMPARISON OF SLAM FRAMEWORKS

Recent SLAM systems for indoor embedded use were compared to find the most suitable approach. ORB-SLAM3 (Oriented FAST and rotated BRIEF) is highly accurate (monocular/stereo/RGB-D, can fuse IMU) but requires a powerful CPU/GPU to run in real time; it “outperforms others in accuracy” on desktop hardware [13]. VINS-Mono and other VIO systems (Visual-Inertial Odometry) use inertial data to improve robustness, but still strain embedded CPUs [14]. DSO/SVO (Semi-/Direct Sparse Odometry) are direct methods (no feature extraction) that can run on grayscale cameras; they track well on textured scenes but easily drift or fail in low-texture or changing light [15]. In one study on an Nvidia Jetson TX1, DSO had much higher drift (Absolute Trajectory Error RMSE ≈0.46 m) than ORB-SLAM (≈0.17 m) or RTAB-Map [15]. RTAB-Map is a graph-based SLAM that supports RGB-D or stereo and loop closures in ROS2; it is widely used for robotics and can run on CPU-only boards. In the same Jetson test, RTAB-Map achieved one of the lowest errors (≈0.16 m) and compared favorably with ORB-SLAM [15]. RTAB-Map was chosen for our walker prototype because it supports RGB-D input, is ROS2-ready, and has proven performance on embedded platforms [16]

3 SYSTEM COMPONENTS

In this section, we outline the system architecture for our indoor mapping solution, featuring a robust integration of hardware and software components. The Nvidia Jetson Orin Nano and Stereolabs ZED Mini provide the necessary computational and sensory capabilities. The ROS 2-based software stack orchestrates data processing and communication, enabling real-time map generation via Visual SLAM.

3.1 Hardware

Nvidia Jetson Orin Nano: Selected for its balance of compute performance (up to 67 TOPS at 25 W) and compact form factor. The single-board computer’s (SBC) Ampere GPU generalizes to various parallel SLAM tasks, while its ARM CPU cores handle ROS2 middleware and peripheral integration.

Stereolabs ZED Mini: A stereo camera providing synchronized 1080p RGB streams at up to 30 fps and depth maps via hardware disparity calculation. It features a built-in IMU (6-axis gyroscope + accelerometer) at 800 Hz sampling, facilitating visual-inertial odometry.

Walking Aid Platform: A standard four-wheel walking aid instrumented with a rigid mount for the camera and an under-seat housing for the Jetson Orin Nano. Power is supplied via a portable battery capable of a stable 20 V/5 A output (per USB-PD profile).

Smartphone: A regular Android smartphone was selected for wireless and convenient visualization of the SBC’s desktop.

The fully assembled walking aid platform can be seen in Figure 2. The SBC is mounted in a specially designed device carrier under the seat. The stereo camera rests in a holder on the bend of the left handle from the user's perspective.

3.2 Software

The software architecture mainly focuses on ROS 2 (Humble Hawksbill). It provides Data Distribution

Service (DDS)-based publish–subscribe messaging, node lifecycle management, and real-time QoS configuration. For camera the ZED Wrapper is an official driver, packaging the ZED SDK into ROS2 nodes, exposing topics for left/right RGB images, depth images, point clouds, IMU data, and visual-inertial odometry. With RTAB-Map, a ROS2 node encapsulating the RTAB-Map core functions. It subscribes to camera and odometry topics, executes SLAM threads internally, and publishes 2D occupancy grids, 3D point clouds, and pose trajectories. Rviz2 is used for visualization and real-time monitoring of SLAM outputs, including map rendering and trajectory display.



Figure 2: AktiMuW walking aid platform with stereo camera and SBC mounted under the seat.

4 PRELIMINARY WORK

Initial map outputs exhibited warped and misaligned point clouds. Inspection of the ROS2 transformation tree revealed the absence of a transform edge between the base_link and zed_left_camera_optical_frame, preventing correct pose propagation. Additionally, the ZED optical frame conventions differed from ROS's REP-103 [17] conventions, causing rotated axes to be interpreted incorrectly.

4.1 Frame Correction

A zero-offset static transform was published to connect base_link to zed_left_camera_optical_frame:

```
ros2 run tf2_ros
static_transform_publisher 0 0 0 0 0 0
base_link zed_left_camera_optical_frame
```

This closed the TF gap, but the point cloud remained rotated as seen in Figure 3.

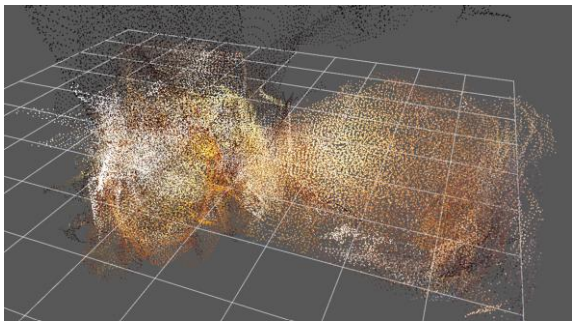


Figure 3: Distorted point cloud of a room after a 360° horizontal camera turn.

4.2 Axis Alignment

After examining the optical frame conventions of ROS2 and the camera, it became apparent that there is a discrepancy in the alignment of the optical axes (see Table 1).

Table 1: Comparison of ZED Wrapper and ROS2 Optical Frame Conventions and required Transformation.

Axis	ROS2 Optical Frame Convention	ZED Wrapper Optical Frame Convention	Required Transformation
X / Roll	Forward	Right	Right (ZED) → -90° → Forward (ROS2)
Y / Pitch	Left	Down	Not required due to other applied transformations
Z / Yaw	Up	Forward	Forward (ZED) → -90° → Up (ROS2)

The camera's optical axes require 90° (−π/2 radians) rotations about the roll and yaw axes to align with ROS2 conventions.

Additionally, the camera center sits approximately 90 centimetres above the walking aid's base. The final static transform command was:

```
ros2 run tf2_ros
static_transform_publisher 0 0 0.9 -
1.5708 0 -1.5708 base_link
zed_left_camera_optical_frame
```

After this update, the point cloud aligned correctly with the physical environment as seen in Figure 4:

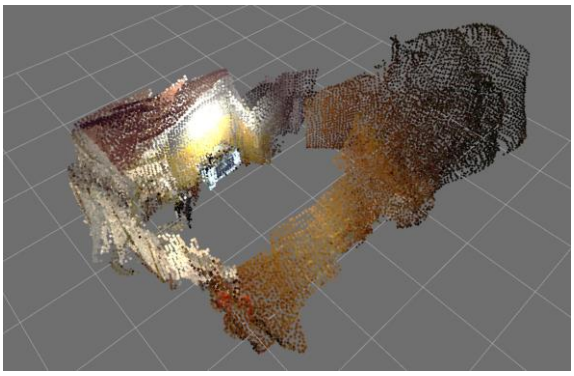


Figure 4: Corrected point cloud of a room after a 360° horizontal camera turn.

4.3 Selection of a Test Environment

The selected test environment is intended to resemble a living environment due to its varied structure and arrangement. A 47.52 m² office space, rich in differentiable characteristics (features), alternates with a 25.2 m² feature-poor entrance hall with complex geometry, which leads into further small bathrooms as seen in Figure 5.



Figure 5: Floor plan of the selected test environment.

Another distinctive characteristic is that the office space is situated 73 cm above the entrance hall, which means that the mapping algorithm is also required to overcome a certain height difference.

5 MAPPING RESULTS

As mentioned beforehand, the entrance hall and the two bathrooms have very few distinctive features, so this area of the test environment was primarily used for the baseline performance test and optimization process.

5.1 Baseline Performance

With the default settings (camera angle 0°, no depth limit, default settings for RTAB map functions), the initial mapping in the entrance hall exhibited several deficiencies as seen in Figure 6.

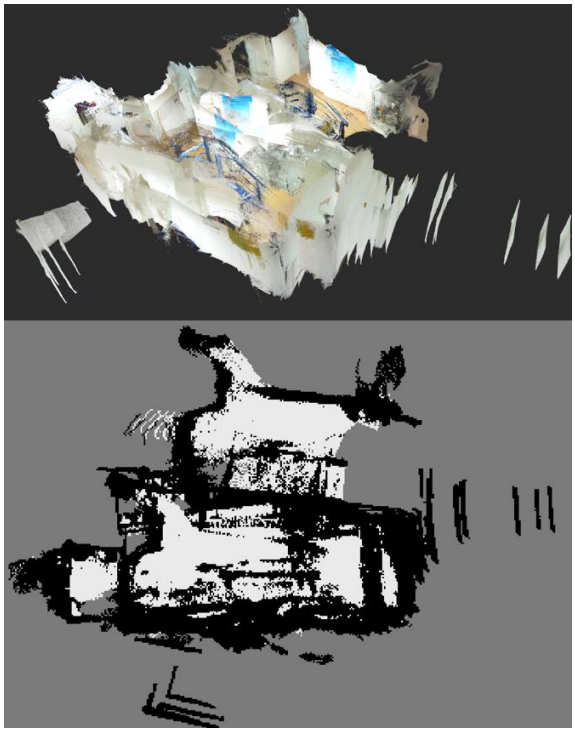


Figure 6: 3D point cloud and 2D occupancy grid with default settings.

Comparing reality vs. reconstructed map the main weakness is about:

1) Repeated Walls: Consecutive walls were often rendered multiple times in slightly shifted positions, creating "ghost" wall artifacts in the 3D point cloud and the 2D occupancy grid.
2) Poor Corridor Geometry: The long corridor segment was barely recognizable in outline, but

walls failed to align properly, leading to kinks and misalignments that did not match the actual room geometry.

3) Loss of Feature Tracking: In particularly difficult to differentiate areas, such as the bathrooms, feature tracking was often discontinued, which required the effort of identifying the last camera view detected.
4) Loop-Closure Gaps: Upon walking a closed loop, no automatic closure of the map occurred.

5.2 Experimental Challenges

During the baseline experiments, several challenges emerged that significantly affected SLAM performance on the walking aid platform:

- Reflective and low-texture surfaces: Glossy floor tiles and plain, bright bathroom walls provided very few reliable features, which led to tracking loss and occasional map discontinuities.
- Repetitive corridor geometry: Long corridors with visually similar wall and floor patterns caused perceptual aliasing, resulting in false loop-closure matches and duplicated wall segments.
- Dynamic disturbances: Moving people occasionally entered the scene, corrupting stereo matches and temporarily degrading odometry estimation.
- Illumination changes: Transitions between rooms with different lighting conditions introduced exposure artifacts, reducing feature matching robustness.

5.3 Optimized Result

After systematic parameter tuning, a set of parameters could be found that enabled a stable mapping result:

- Camera Angle: Tilted downward by 20° to the ground to minimize ceiling and window capture.
- Depth Range Limit: Reduced to a maximum of 5 m to exclude noisy distant measurements and reduce point-cloud clutter.
- Odometry: Switching from purely ZED Mini IMU-based odometry to visual-only odometry considerably improved path tracking performance.
- Feature Detector: Switched from GFTT/ORB to KAZE to enhance feature extraction in unvaried environments like brightly tiled bathrooms.
- Feature Tracking and Loop-Closure Optimization: Lowered the minimum number of inliers for feature matching (Vis/MinInliers) from 20 to 8 and raised the maximum number of features extracted per image (Vis/MaxFeatures) from 500 to 2000, enhancing image recognition and therefore loop-closure detection as seen in Figure 7.

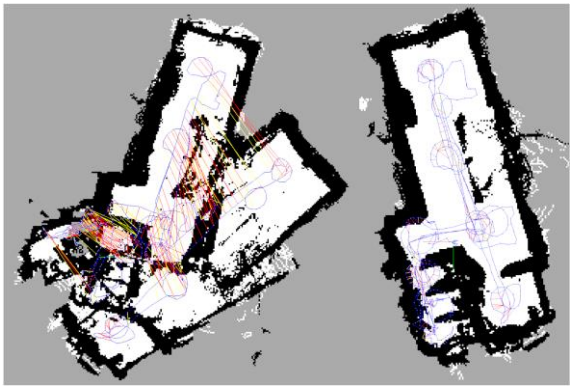


Figure 7: 2D occupancy grid before (left) and after loop closure (right).

5.4 Application to the Room Complex

The optimized mapping parameters were next applied to the full room complex, encompassing both the feature-rich office space and the adjacent entrance hall with the two bathrooms. A single uninterrupted path was executed, starting with the entrance hall and the bathrooms and proceeding to the office via stairway transition.

Despite the low-texture bright and in places tiled walls, the entrance hall and bathrooms were mapped without major gaps. The 20° camera tilt directed more features toward the floor-wall boundary, enabling the SLAM algorithm to maintain tracking in these challenging areas. The height difference between the entrance hall and office level was captured as a smooth vertical offset in the 3D map, with the staircase geometry correctly represented as seen in Figure 8.

As also seen in Figure 8, the office area was reconstructed with high fidelity. Desks, chairs, and shelving units appeared as distinct clusters in the 3D point cloud. The 2D occupancy grid accurately delineated walking aisles between desk clusters as seen in Figure 9.

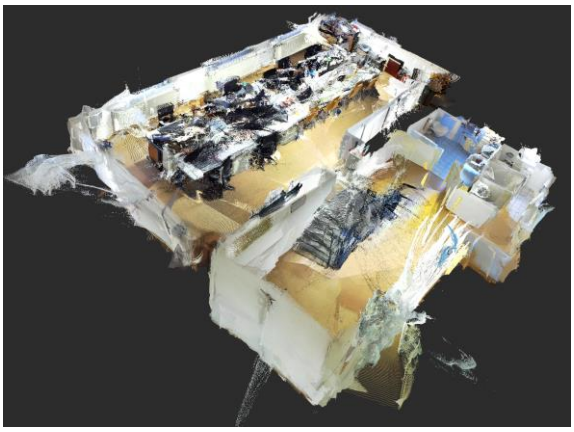


Figure 8: 3D point cloud of the complete test environment with visible offset between room levels.

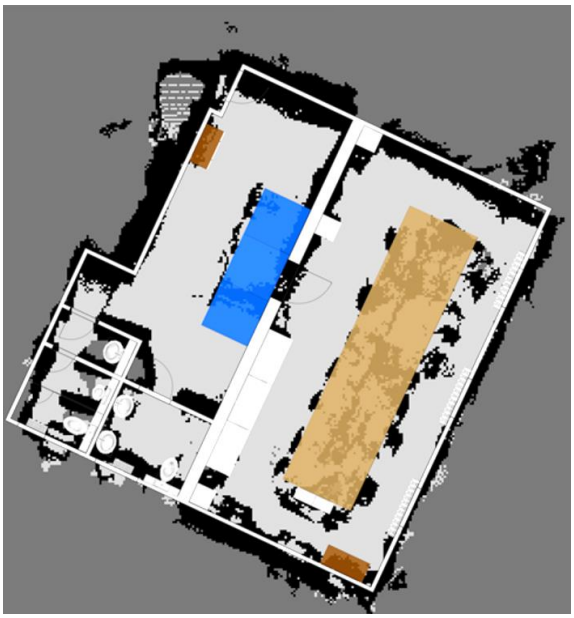


Figure 9: 2D occupancy grid of the complete test environment with validation against the floor plan.

Each rotation at the waypoint returned successfully closed prior loops, resulting in a fully connected 2D grid of the entire complex. No discontinuities were observed at room transitions or while overcoming the staircase.

6 CONCLUSIONS

Reliable indoor mapping is a critical enabler for navigation in smart assistive devices. This work shows that, even on a resource-constrained mobile platform like a smart walking aid, Visual SLAM can deliver accurate, consistent maps, provided that the system is carefully calibrated and adapted to real-world constraints.

By combining a stereo camera, an SBC and the open-source RTAB-Map framework, a full SLAM pipeline was deployed and optimized for real-time use. Key modifications, including depth limiting, camera tilt, axis-aligned TF corrections, and parameter tuning, proved essential for handling texture-poor environments, minimizing mapping artifacts, and preserving loop consistency.

The system did not just perform thoroughly in a controlled test zone; it successfully scaled to a full floor, including stairs, bathrooms, and low-feature areas. The resulting maps were geometrically accurate, loop-closed, and complete, forming a solid foundation for downstream tasks like path planning and user guidance.

These findings demonstrate that high-quality indoor SLAM is within reach even for compact, affordable assistive systems. With careful tuning, visual sensing alone can match the reliability once reserved for more expensive LIDAR-based setups. Future work on this topic will include the implementation of user-interface-guided real-time navigation.

6 FUTURE WORK

Future work will focus on transforming the presented SLAM-based mapping system into a fully integrated indoor navigation solution for assistive walking aids.

One important step will be the implementation of a user-friendly interface that allows elderly users to request navigation assistance and receive intuitive visual or haptic guidance. To further increase safety, the system will be extended with real-time obstacle detection and avoidance features, enabling reliable operation even in highly dynamic environments with moving people or pets.

Energy efficiency is another priority, as optimizing computation pipelines and sensor duty cycles will be essential to ensure extended operating times on battery-powered platforms. In addition to on-device improvements, the integration of Bluetooth Low Energy (BLE) beacons and other infrastructure-based localization technologies will be investigated to provide absolute positioning in large or feature-poor areas, such as open corridors or lobbies, where Visual SLAM performance can be limited. Furthermore, enriching geometric maps with semantic labels – for example, identifying doors, furniture, or hazard zones – offers the potential for context-aware navigation and improved caregiver support.

Finally, scalability will be addressed through the exploration of cloud-based map optimization and multi-floor map sharing, enabling operation in complex care facilities without overloading the embedded platform. These developments aim to evolve the current prototype into a robust, comprehensive navigation solution that seamlessly integrates on-board SLAM with infrastructure support, offering greater autonomy and safety to users.

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Intelligent Goose Nest: Review, Development and Evaluation of Initial Results for Design Concepts

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Keywords: Goose Nest Design, Egg Collection, Animal Welfare, Mechanical Entry System, Modular Construction.

Abstract: This work presents the conception and prototyping of a modular goose nest system intended as a first step towards an intelligent, sensor-based nesting environment. Motivated by the lack of suitable laying sites in deep-litter and raised-floor systems, the study focuses on the mechanical design of nest frames, entrance mechanisms, floor geometries and passive egg-collection elements and evaluates their acceptance under farm conditions. Two wooden frame prototypes with different door and floor configurations were constructed and tested with a small group of geese. Nest use and laying behaviour were monitored continuously via video and analysed through manual event annotation (approach, entry, exit, egg laying, and interactions with structural elements). The experimental results show that, although the frame construction and basic floor concepts are mechanically robust and suitable for barn environments, the tested entrance mechanisms substantially reduced nest acceptance. Across all phases, only 1 of 40 eggs was laid in the nest, and none were successfully transported to the collection tray. Video analysis linked this low use primarily to aversive features of the side-hinged door with magnetic stop (noise, partial closing, transient trapping) as well as to strong group-nesting tendencies at floor-laid eggs outside the nest. Rather than demonstrating a ready-to-use solution, the present study identifies critical design constraints and behavioural failure modes that must be addressed in subsequent development stages. The findings highlight the need for quieter, low-resistance and low-risk entrance designs, mechanically robust yet chew-resistant materials, and management strategies that prevent the formation of external group nests. These lessons provide a concrete basis for the next generation of intelligent goose nests and for more targeted experimental evaluation of integrated sensor systems.

1 INTRODUCTION

Conventional goose husbandry presents numerous challenges, particularly in terms of monitoring egg-laying, ensuring hygienic conditions, and maintaining animal welfare [1]. Traditional goose husbandry systems, such as deep-litter systems, offer hygienic advantages as excrement and excess water fall directly into a pit or onto the floor beneath. However, such systems often lack suitable, species-appropriate nesting environments, leading to increased instances of floor eggs [2][3]. As [4] highlights, these systems struggle to provide optimal conditions for egg-laying. Social and reproductive behaviors, including group nesting tendencies, further complicate these issues and impact nest acceptance. These behaviors, along with the natural tendencies of geese to form external group nests, are crucial factors in the design and evaluation of artificial nesting systems [5]. One commonly applied method for identifying individual laying geese is trap nesting, which allows targeted selection and culling. Typically, this involves installing a mechanical door on a standard nest box that closes once the goose enters, preventing escape until manually released. While effective under controlled conditions, this method proves unreliable when geese lay eggs in alternative locations, especially in deep-litter systems, where multiple potential nesting sites complicate individual egg attribution [3].

An alternative approach involves manually inspecting geese in the evening to detect those ready to lay. Identified individuals are then placed in separate nesting compartments equipped with locking doors. This labor-intensive process is usually conducted four to seven days per week. Egg counts are then estimated proportionally. In more intensive systems, raised flooring is employed to optimize space and reduce bedding requirements. Commonly used materials include wooden slats or expanded metal/plastic grids. These setups offer hygienic advantages, as excrement and

excess water fall directly into a pit or onto the floor beneath. However, while efficient in terms of space and maintenance, such systems often lack suitable, species-appropriate nesting environments, as [6] describe, making them less ideal for natural egg-laying behavior.

To address these shortcomings, the present study focuses on the development of a structurally optimized, modular, and automatable goose nest that facilitates secure, species-appropriate egg-laying while enhancing monitoring and collection processes.

Figure 1 illustrates the overall operational workflow of the intelligent nest system; from the moment a goose enters the nest to the final storage of processed event data. The sequence begins with controlled nest access through the mechanical entry system, followed by detection of the animal's presence through load cell measurements. Once inside, the goose is identified via RFID, enabling individual attribution of subsequent events. A characteristic pattern in the weight signal indicates the laying of an egg, which triggers the recording of relevant sensor data. These data are then evaluated algorithmically to link the detected egg to the identified animal. After validation, the egg is marked with its corresponding identifier, and all information is transferred to the database for long term storage and later analysis. The diagram highlights the coordinated interaction between mechanical elements, sensor systems, microcontrollers, and backend infrastructure, illustrating how local detection and global data processing together form the foundation of the intelligent nest system.

This paper reports on the first project phase, which focuses on the conception, construction and behavioural evaluation of mechanical nest prototypes, including frame, entrance mechanisms, floor designs and egg collection elements. The electronic architecture shown in Figures 1 and 2 has been implemented at the prototype level but is not yet evaluated experimentally in this work. A subsequent project phase will systematically assess the performance of the load cell subsystem, the RFID based identification, the database backend and the connected output devices under farm conditions.

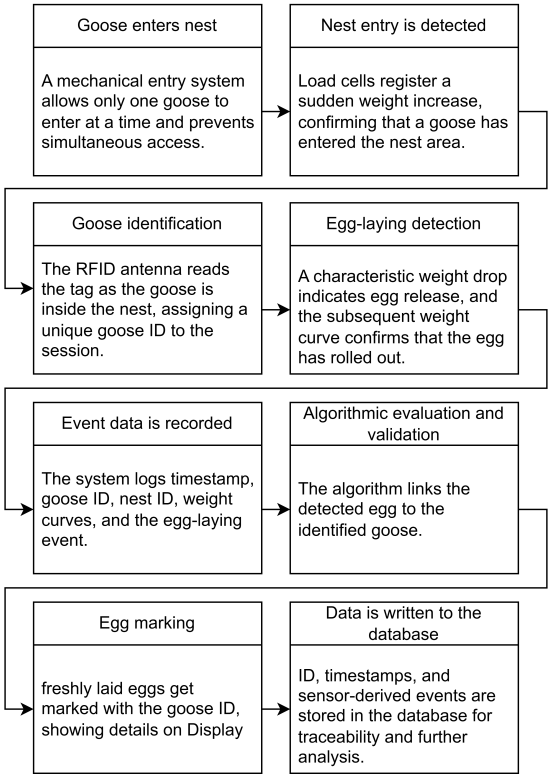


Figure 1: Overview of the functional workflow of the intelligent nest system, illustrating the sequence from controlled nest entry and sensor-based event detection to animal identification, egg attribution, marking, and database integration.

2 GOOSE ELECTRONIC AND MECHANIC SYSTEM DESIGN

2.1 Electronic System Design

Figure 2 illustrates the system architecture underlying the intelligent nest prototype, highlighting the interaction between local sensing components and the external processing infrastructure. Inside the nest, the RFID reader and the load cell module collect identification and weight data, which are transmitted to a central database computer for event reconstruction, validation, and storage. Based on the processed information, the system triggers two peripheral units located outside the nest: an automated marking device that applies a unique identifier to each egg, and a user display that presents real-time information such as the laying sequence or animal-specific events.

This architecture separates environmental sensing inside the nest from computational tasks and actuator control outside, allowing robust operation in barn conditions while ensuring reliable communication and data flow across all system components. In the present project phase, this electronic architecture is defined conceptually and serves as the target framework for later integration. The practical work reported in this paper therefore focuses on the design and behavioural evaluation of the key mechanical components that support the electronic system, namely the nest frame, entrance doors and ramp, floor geometries and passive

egg collection paths. The detailed implementation and experimental testing of the electronic subsystems (load cell and RFID units, microcontroller modules, communication links and backend processing) will follow in subsequent project phases, building on the mechanical baseline established in this study.

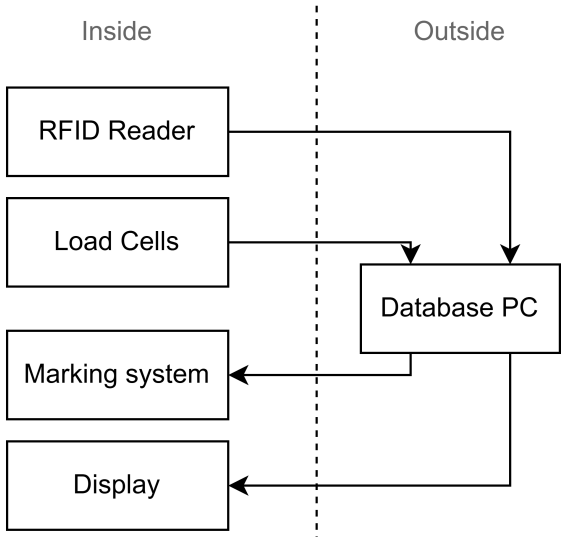


Figure 2: System architecture of the intelligent nest prototype, showing internal sensing components (RFID reader and load cells) and external processing units (database PC, marking system, and display) interconnected through bidirectional communication.

2.2 Frame Design

The primary objective of the frame design is to create a safe, comfortable, and functional environment for egg-laying. The nest must allow geese to enter and exit freely while preventing multiple geese from occupying the same nest simultaneously, thereby reducing stress and disturbances during egg-laying. Additionally, the frame should accommodate sensors, such as load cells, for monitoring purposes. As [7] points out, lightweight construction principles are key in ensuring both stability and ease of manufacturing. Therefore, both wooden and aluminum frame variants were designed with a two-level structure: the upper section serves as the nesting area, while the lower section houses technical components.

Where possible, the use of electrical components was avoided to minimize system complexity, eliminate the need for wiring, and facilitate thorough cleaning. The frame must also withstand high humidity, dust, and frequent exposure to water and detergents [6]. Structural integrity and long-term material durability were thus key design criteria.

2.2.1 Wooden Frame Design

The first frame design is constructed from wood and consists of two side walls, a rear wall, and two front walls, as illustrated in Figure 3.



Figure 3: Wooden frame design.

The walls are connected using wooden battens, with four along the bottom and two at the top, to ensure structural integrity. Since the material is wood, the walls are fastened using self-tapping screws to provide a stable and durable connection. Additionally, a handle and a window are integrated into one of the side walls. A horizontal batten at the top adds further structural stability.

2.2.2 Aluminum Profile Frame Design

The aluminum frame is constructed from aluminum profiles cut to various lengths and assembled into a stable structure. The individual profiles are joined using screws to ensure structural robustness (see Fig. 4).

The wooden frame is the preferred option due to its simplicity, ease of construction, and integration of practical features like a handle and window for accessibility. It provides sufficient structural integrity using battens and screws, aligns well to minimize system complexity, and allows easier customization or adjustments during use.

2.3 Entrance Mechanism Design

2.3.1 Gravity-Activated Mechanism (Option 1)

The developed entrance system features an automatic door mechanism based on a combination of gravitational force, leverage, and a two-part flap door. Before entry, the door remains open. When a goose steps onto the inclined, pivot-mounted floor, the resulting downward motion activates a mechanism that automatically closes the door.

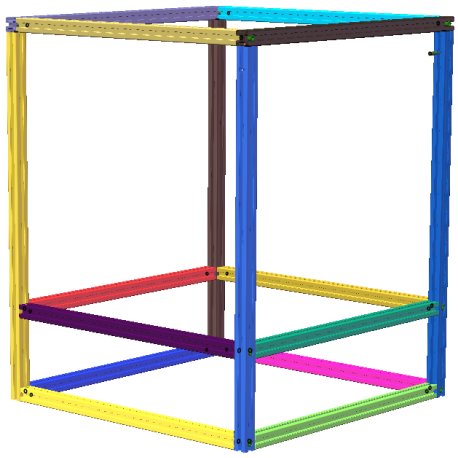


Figure 4: Aluminum profile frame design.

To ensure that the goose inside the nest can exit while preventing additional geese from entering, a split-door design with a restricted hinge angle is used. This construction allows the door to open only outward from the inside. A torsion spring returns the door to its initial position after the goose exits, enabling con-tinuous operation. The floor is pivotally mounted at a fixed point on the frame, while the door is attached via a rotary joint. The mechanical linkage between floor and door is currently under development; a linkage rod system is being considered as a potential transmission mechanism.

2.3.2 Gravity-Activated Mechanism (Option 2)

To improve weight-measurement accuracy, the nest floor in Option 2 was designed as a vertically movable platform that remains level at all times, independent of the door position. This configuration not only enhances measurement fidelity but also provides a more stable and comfortable surface for the geese, particularly during egg laying.

The door movement and floor motion are mechanically coupled through a guided linkage system. The lower linkage rods are mounted on rails integrated into the frame, allowing both controlled vertical displacement of the floor and coordinated motion of the door. The overall kinematic concept is illustrated in Figure 5, which shows the complete 3D model of the entrance mechanism.

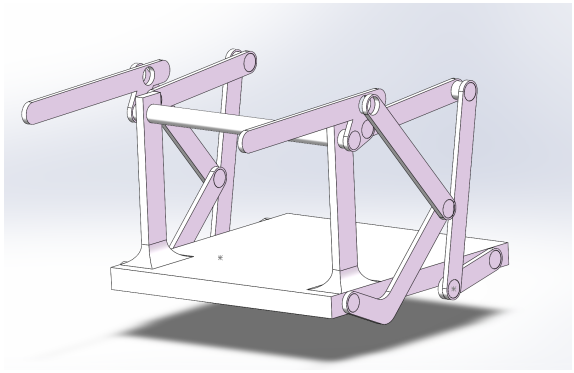


Figure 5: 3D model of the gravity-activated entrance mechanism (Option 2).

2.3.3 Top-Hinged Mechanism

The design attaches the door to the frame using a rotational axis or a hinge, allowing it to rotate freely. The door can be mounted directly on the axis or hinge, or connected via a connector to facilitate easy replacement. By appropriately determining the center of gravity, the door remains at rest with the short side pointing downward and the long side open. As shown in Figure 6, a schematic representation of the door in its open and closed positions is provided.

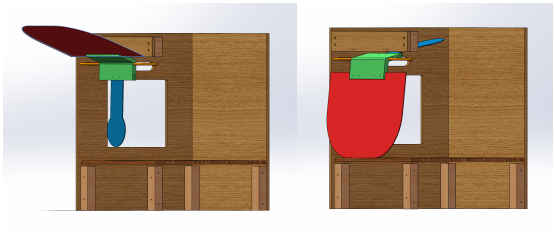


Figure 6: 3D model of the top-hinged door mechanism: opened (left) and closed (right).

2.3.4 Side-Hinged Mechanism

As shown in Figure 7, the side-hinged door mechanism is laterally mounted to the frame via a hinge or rotational axis. Two connected door panels form a right-angled door structure functioning as a single unit.

This design allows the inner door to open when a goose enters the nest, while the outer door automatically closes as a result of the connected geometry. Additionally, magnets are incorporated to hold the door in place when the opening angle is insufficient, ensuring that the door either remains open or closes automati-

cally depending on its position. This construction not only simplifies the entry and exit process for the geese but also effectively prevents unintended opening or closing of the door, thus enhancing both usability and structural stability.

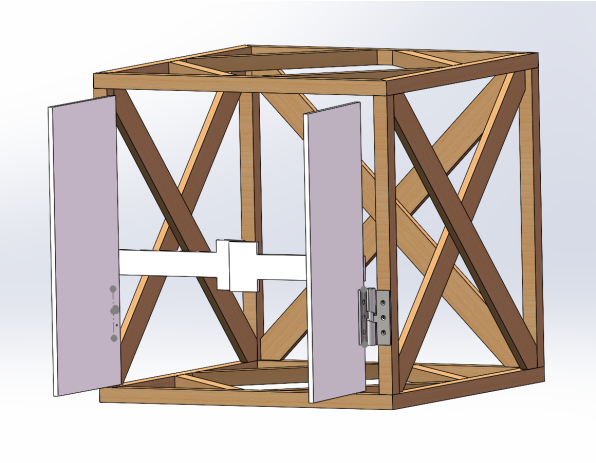


Figure 7: Side-swing door mechanism.

2.3.5 Inclined-Movement Floor Module

The inclined-movement floor module integrates the entrance control directly into the floor structure using a pivot-mounted plate (Fig. 8). When a goose steps onto the plate, it initially remains horizontal. As the animal moves forward and crosses the pivot axis, the rear part of the plate lowers to form a shallow ramp, while the front part rises and blocks the entrance. This automatic transition prevents additional geese from entering once the nest is occupied. Compared to more complex gravity-activated linkage systems, the hinged mechanisms described earlier (top-hinged and side-hinged doors) provide simpler, more robust and easier-to-maintain solutions. These alternatives therefore remain the preferred options for subsequent prototype stages.

2.4 Nest Floor Design

The floor must provide a stable surface for the geese while enabling reliable passive egg transport. A slight inclination is required to ensure that eggs roll toward the collection area without compromising the animals' mobility or comfort.

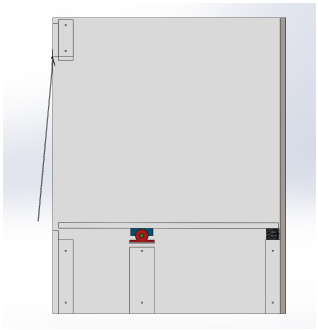


Figure 8: Inclined-movement floor module with pivoting plate.

2.4.1 Rear-Opening Floor Panel

The rear-opening design (Fig. 9) uses a central depression and a gentle rearward incline that guides eggs naturally toward the collection opening. This approach avoids complex bowl-shaped geometries, simplifies manufacturing, and reduces material and tooling requirements. It also supports easy installation and maintenance while ensuring safe and reliable egg flow, making it well suited for large-scale farm environments.

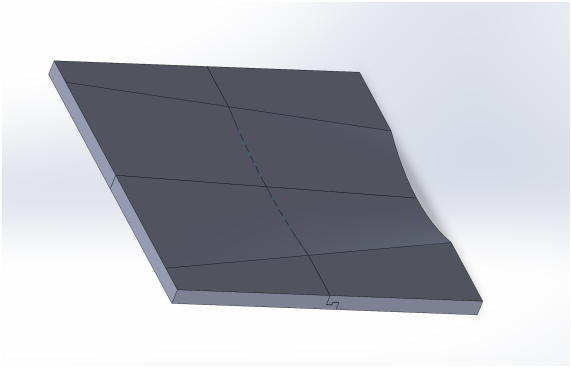


Figure 9: Rear-opening floor panel.

2.4.2 Center-Drain Floor Panel

The center-drain variant (Fig. 10) guides eggs directly through an opening in the floor, r educing the need for side or rear cut-outs. While production is straightforward, the design requires a large opening (130–140 mm) to accommodate goose eggs. This creates a safety risk, as birds may step into the hole and potentially injure themselves, particularly when entering or moving inside the nest.

For these reasons, the rear-opening panel is preferred: it transports eggs effectively without introducing injury hazards and offers simpler construction, lower costs, and improved long-term practicality.

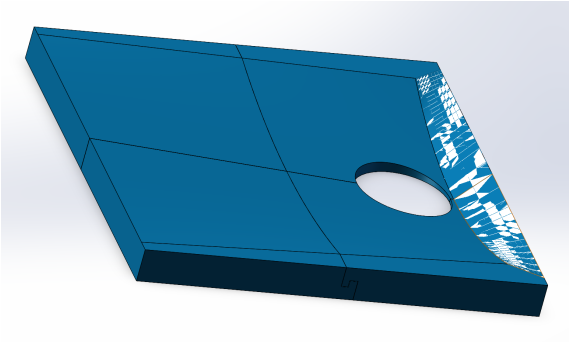


Figure 10: Center-drain floor panel.

2.5 Egg Collection Tray Design

According to the functional requirements, goose eggs should roll down from an elevated position in a row and remain undamaged. As part of the nest space is reserved for technical instruments, the eggs descend from above and eventually reach the egg collection tray. Therefore, a reliable cushioning mechanism must be installed at the end of the tray to prevent damage from impacts or excessive rolling speed. Depending on the floor design, two different rail systems are used. If the egg collection hole is located on the floor, the egg tray can be positioned at the front, underneath the ramp. This configuration saves space and offers a clean solution. Figure 11 shows the front tray layout as a visual representation of this concept.

Although this method is effective, it is less practical for a rear-opening system. If such a design were used, the eggs could fall vertically due to the curvature of the drop pipe, increasing the risk of breakage. Therefore, an alternative design is implemented. This version uses a flatter incline, which is gentler on the eggs. However, the main trade-off is increased space requirements. This solution is illustrated in Figure 12, showing the side-mounted tray configuration.

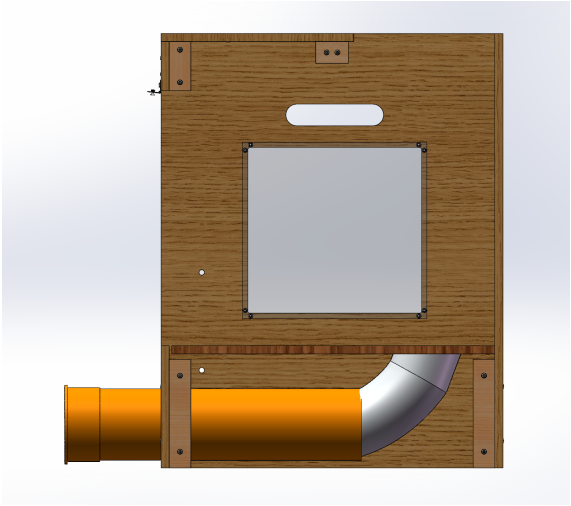


Figure 11: Front egg collection tray.

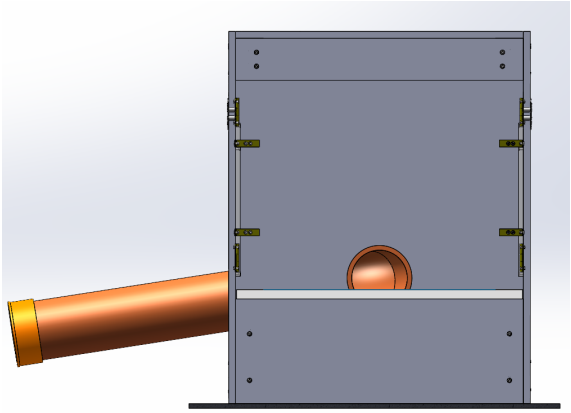


Figure 12: Rear egg collection tray.

3 NEST DESIGN SELECTION

3.1 Frame Material Selection

The choice of frame material had to consider corrosion resistance, moisture resistance, low weight, mechanical robustness, and cost-efficiency, as [8] discusses in their work on material properties. Based on these criteria, several materials were compared (see Table 1).

Table 1: Comparison of different materials [8], [7].

Material	Corrosion Resistance	Density [g/cm³]	Hardness [HB]	Price [€/kg]
Stainl. Steel	Excellent	7.8	200	16
Al-Alloy	Good	2.7	60–150	20–30
Wood	Poor	0.4–0.9	70	0.5–1
Iron	Poor	7.8	80–100	0.5–1

For the initial design of the goose nest frame, aluminum profiles were modeled to allow for rapid structural assessment. Due to the high cost, the final material choice was laminated wood panels. This material offers a good balance of stability, ease of process-

ing, environmental friendliness, and cost-effectiveness. Compared to steel, it is lighter; compared to plastics, it is more durable and mechanically stronger. With appropriate moisture protection treatment, the frame structure remains stable and durable even in humid and dusty environments.

3.2 Entrance Mechanism Selection

Following a comparative analysis of various entry mechanisms and considering the design requirements, two mechanisms were selected: a top-hinged door and a side-hinged door. More complex solutions, such as a bottom-door linkage mechanism or a side door with a diagonally movable floor module, were rejected due to their structural complexity, implementation challenges, and cleaning difficulties. In contrast, the top-hinged and side-hinged doors offer a simple, robust design based on basic mechanical principles. They ensure reliable functionality, enable cost-effective manufacturing and easy cleaning, and thus meet the practical requirements of a functional goose nest.

3.3 Floor and Egg Collection Method Selection

Following the selection of the top-hinged and side-hinged doors, suitable floor and egg collection systems were defined to ensure unobstructed access and reliable passive egg transport. Nest 1, equipped with a top-hinged door, uses a rear-opening floor panel that guides eggs from a shallow central depression directly into a subfloor collection tube. This enables rapid egg removal and reduces the risk of breakage or pecking. Nest 2, featuring a side-hinged door, employs a floor panel that directs eggs through an opening in the rear wall onto a gently sloped collection surface. This maintains free movement for the geese while ensuring a short and safe rolling path. Both systems rely solely on passive mechanical elements. By avoiding electronics in the collection area, they remain robust against moisture and contamination, reduce maintenance requirements and provide long-term operational reliability under barn conditions.

4 MANUFACTURING

4.1 Frame Construction

The frame is constructed from multilayer plywood for its strength and stability. Fastening is achieved using wood screws and reinforcing wooden battens. L-shaped metal brackets are added to all corners to enhance impact resistance and prevent deformation caused by goose activity.

Before assembly, panels are precisely cut into structural parts: two side walls, one rear, and one front wall. Edges are sanded to avoid injury. Window outlines are marked and 4 mm relief holes are drilled at each corner to prevent cracks. The window opening is then cut and sanded. An acrylic pane is mounted using adhesive and corner screws.

For the handle, two 20 mm holes are drilled and connected with a jigsaw cut; all edges are smoothed. Panels are laid flat pre-assembly for alignment. Vertical accuracy is ensured with a square, and battens are mounted flush to the side w alls. The finished structure is impact-tested, confirming material strength and stability under typical goose movements.

After the frame was completed, several functional tests were conducted to evaluate the practical suitability of the designed goose nest. First, a load test was performed to ensure that the structure could withstand the weight of the geese and their movements. This was followed by a mechanical safety test, specifically checking for sharp edges and potential injury risks for both the animals and personnel during assembly, disassembly, or cleaning. A stability test was carried out to assess resistance to vibrations or sudden shocks. Additionally, the corrosion resistance of the materials used was examined to ensure long-term durability in a humid barn environment. Finally, a light transmission test was conducted to verify whether the transparent or semi-transparent side walls allow sufficient light into the nest without permitting direct sunlight.

4.2 Nest 1

4.2.1 Top-hinged Door Mechanism with Servo Motor

Nest 1 includes a top-hinged door with a motor-operated locking bolt, as seen in Figure 13. A servo motor is installed 375 mm above the ground on the right frame side. When weight is detected by load cells, the motor rotates the locking bolt 90°, preventing the door from opening inward. This ensures only one goose enters at a time. The motor cable runs externally along the frame and beneath the nest floor to avoid goose interference.

4.2.2 Egg Collection Area

This nest features a rear floor opening for egg collection. A 126 mm diameter hole is cut for the collection

tube, considering tolerance. A 50 mm-thick extruded polystyrene (XPS) foam plate is added, angled toward the opening to guide eggs smoothly into the tube. A flexible pipe runs under the floor, through the rear panel, and extends beneath the ramp for safe egg transfer.

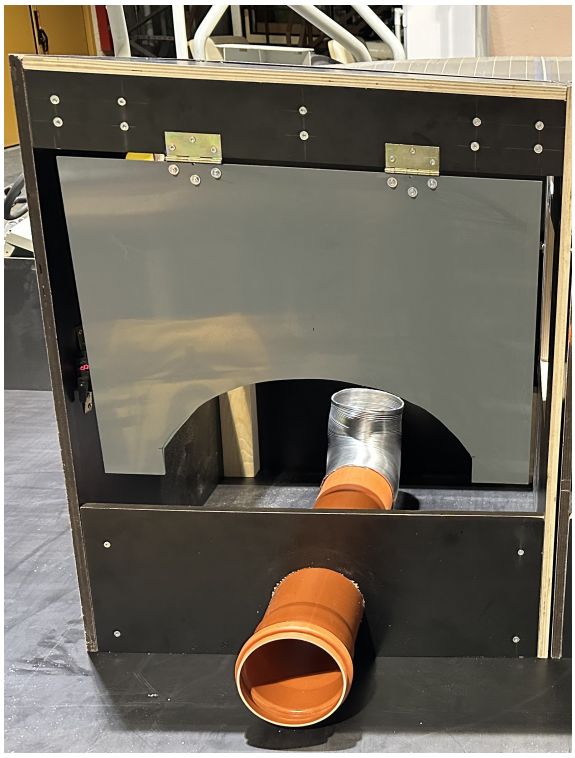


Figure 13: Configuration of Nest 1 with top-hinged door and center-drain floor panel.

4.3 Nest 2

4.3.1 Side-hinged Door Mechanism

Nest 2 uses a side-hinged door system. Panels are cut to shape, and each side includes an outer and inner door. The outer doors are attached to the frame; inner doors are mounted onto them using 90° metal brackets, as illustrated in Figure 14.

Magnetic stops are added to control door positioning (see Fig. 15). When a goose pushes the inner door, it swings inward and is held open by the magnet, while the outer door remains closed to prevent escape or unintended entry.

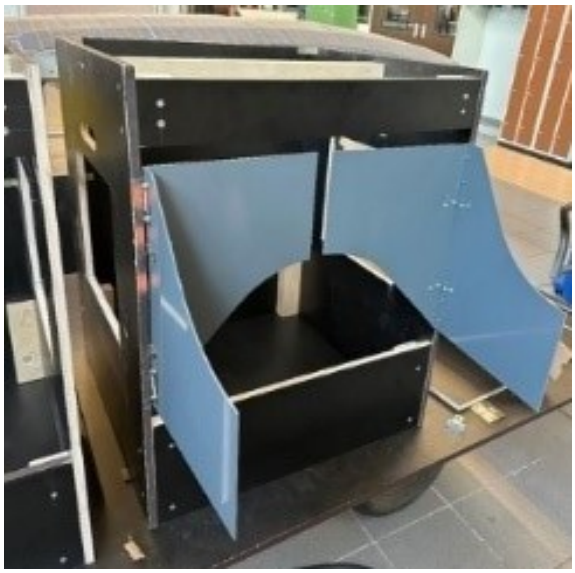


Figure 14: Configuration of Nest 2 with side-hinged door and rear-opening floor panel.



Figure 15: Magnetic stops of the side-hinged door mechanism.

4.3.2 Egg Collection Area

A 126 mm opening is cut into the rear wall for the egg collection pipe. Two floor panels angled at 110° direct eggs into the pipe, which is supported and aligned by two stabilizing struts. A 50 mm XPS foam layer is added, sloping toward the rear opening to ensure eggs roll efficiently.

4.4 Electrical Component Integration

The load cell is mounted on the underside of the wooden platform, with force transmission established through a beam beneath the floor. Screw holes are countersunk to avoid protrusions and ensure a flush surface. The installation of the load cells and the supporting structure is shown in Figure 16.

In addition to weight measurement, the system incorporates an RFID unit for individual animal identification at nest entry. The RFID reader, antenna and microcontroller are housed together in a dedicated electronics module, which is also shown in Figure 16. The load cell subsystem and the RFID subsystem operate on separate ESP32 microcontrollers, enabling independent acquisition, filtering and timing of their respective data streams. Data exchange between the microcontrollers and the database computer is carried out via MQTT. Each controller publishes its data to dedicated topics, allowing the server to merge information into coherent event structures, associate egg-laying events with individual animals, and communicate with peripheral devices such as the display and automated marking system.

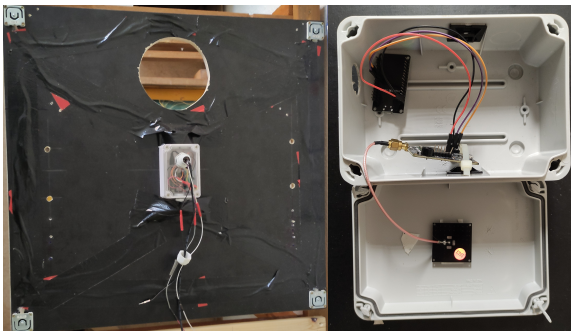


Figure 16: Electronic subsystems of the intelligent nest: load cell assembly beneath the nest floor (left) and RFID module with reader, antenna and ESP32 microcontroller (right).

4.5 Ramp Design

The ramp (see Fig. 17) is 550 mm long and set at an angle of approximately 24.15°, within the recommended range of 20°–25° for goose accessibility. Crosswise anti-slip wooden slats are mounted 50–70 mm apart to enhance traction. The ramp attaches to the nest frame with two hooks for easy assembly and disassembly.

4.6 Experimental Setup and Behavioral Observation

All behavioural tests were carried out in a stable housing with a group of five female geese under routine husbandry conditions. To obtain a precise ground-truth reference for nest use and laying activity, the area in front of the prototype nest and the nest interior were continuously monitored with a fixed video camera operating 24/7 throughout the entire experimental period. The video material was subsequently reviewed and annotated manually. For each goose, all relevant behavioural events were extracted with time stamps and assigned to one of two spatial categories: (i) presence in front of the nest, defined as standing or staying within the approach zone directly in front of the entrance, and (ii) presence inside the nest, defined as all periods during which the animal had fully entered the nest chamber. In addition, each entry and exit event was marked explicitly to reconstruct the exact sequence and duration of visits.

Egg-laying events were identified in the recordings based on characteristic posture changes and the subsequent appearance and position of the egg. For every egg, the approximate time of laying and its final location (inside the nest, rolled to the tray, or outside the nest) were documented. Furthermore, the videos were used to characterise how individual geese interacted with the different entrance mechanisms, including behaviours such as pecking at the door, looking into the nest without entering, hesitating in the approach zone, pushing under partially opened flaps, or reacting to mechanical noises (e.g. the snapping of magnets).

The manually annotated events formed the basis for calculating the cumulative presence times in front of and inside the nest for each goose and experimental phase (Table 2). They also provided qualitative context for interpreting acceptance or avoidance of specific entrance designs and for linking observed behaviours to the mechanical properties of the prototype nests.

5 RESULTS

All tests were conducted in a stable housing with a group of five female g eese. Prior to these tests, the general Nest Frame design was evaluated for safety and acceptance. Nest 1, which used a Center-Drain Floor Panel, posed a potential risk of injury, as the geese repeatedly stepped directly onto the drain. For this reason, Nest 1 was not tested further. The experiments therefore focused on Nest 2, equipped with a side-hinged entrance supported by magnets. In that configuration, several issues became apparent: in some cases, geese triggered only one of the two doors, leaving the other flap closed, or pushed themselves underneath the door without activating the mechanism, as seen in Figure 17. In addition, the snapping noise of the magnets startled some animals and led to reluctance to enter. The Inclined-Movement Floor Module, tested separately as a simple passageway, was accepted without hesitation, with all geese passing over it without observable stress.



Figure 17: Goose only activates one door of the side-hinged entrance mechanism.

Three consecutive experimental phases were implemented to assess acceptance, access behavior, and laying activity as a function of the entrance mechanism: Phase I (24–28 Jan, nest with door including magnetic stop), Phase II (28–31 Jan, nest with door but without magnets), and Phase III (31 Jan–13 Feb, nest body without any entrance mechanism). The quantitative outcomes are summarized in Table 2, which lists for each goose the cumulative time spent in front of the nest and the time spent inside the nest.

Table 2: Cumulative presence times [min:s] in front of and inside the nest across phases.

	Phase I		**Phase II**		**Phase III**	
Goose	Front	Nest	Front	Nest	Front	Nest
G1	03:38	00:00	15:44	00:00	18:42	34:31
G2	00:00	00:00	00:06	20:46	47:33	87:09
G3	03:44	00:00	06:00	05:16	125:32	77:22
G4	01:49	04:19	04:59	62:26	35:14	20:38
G6	04:55	00:00	03:20	00:00	13:24	30:35
Total	**14:06**	**04:19**	**30:09**	**89:28**	**240:25**	**250:15**

In Phase I (door with magnets), only Goose 4 entered the nest, with a total of six short visits amounting to 04:19 min inside. All other animals remained exclusively in front of the entrance without crossing into the nest chamber. The cumulative time spent in front of the nest was low (14:06 min).

During Phase II (door without magnets), a marked increase in nest use was observed. Goose 3 entered the nest twice (05:16 min in total), Goose 2 entered six times (20:46 min), and Goose 4 entered twelve times, reaching the maximum cumulative presence of 62:26 min inside. In contrast, Goose 1 and Goose 6 only remained in front of the entrance without entering. Overall, the cumulative time spent inside rose to 89:28 min, while the total front times more than doubled (30:09 min).

In Phase III (nest body without entrance mechanism), nest use broadened further: all geese entered the nest at least occasionally. Goose 2 accumulated the longest presence (87:09 min across 13 visits), followed by Goose 3 (77:22 min across 21 visits). Goose 1 and Goose 6 showed moderate use (34:31 min across 8 visits and 30:35 min across 7 visits, respectively), while Goose 4 reduced her nest presence to only 20:38 min across 9 visits. In absolute terms, the total front-of-nest time reached its maximum (240:25 min), and the cumulative inside-nest time also peaked at 250:15 min. When normalized by phase length, the average daily presence in front of the nest continued to increase across all phases, whereas the average daily time inside the nest was highest in Phase II and then declined in Phase III, although it remained well above Phase I. This suggests that while approach activity kept rising with prolonged exposure to the structure, the actual time spent inside was most pronounced once the magnets were removed but before the entrance mechanism was fully eliminated.

Beyond the quantitative presence times, the manual video annotations revealed several recurring behavioural patterns across all five geese that are directly relevant for the evaluation of the nest prototypes. First, the entrance proved to be a critical interaction point: all animals were repeatedly observed approaching the nest, inspecting the doorway visually, and withdrawing again without entering. This pattern occurred across all phases and independently of individual differences, indicating that the design and kinematic and mechanical characteristics of the entrance system strongly influence initial acceptance. A second consistent observation concerned the interaction between the geese and the mechanical door elements. In all individuals, at least one event was recorded in which the animal's back or feathers came into contact with a moving or partially closing door wing, and in several cases minor trapping between door components occurred. Such incidents did not result in injury but created brief interruptions in movement, and in at least one individual, subsequent hesitation when passing the doorway. These findings support the quantitative results that the side-hinged construction and the magnetic stop introduced mechanical constraints that reduced acceptance and, in some cases, generated aversive experiences. Across all recordings, the geese also showed pronounced manipulative behaviour directed at structural nest components. The floor mat, ramp surface, and frame edges were frequently pecked, lifted, or chewed, sometimes causing visible damage such as fraying or detachment of adhesive tape. These behaviours indicate that exposed surfaces in the nest vicinity are not only passive load-bearing structures

but are actively used as exploration and pecking substrates, which has direct implications for material durability and safety. Finally, the few eggs laid inside the nest were often not automatically transported out of the nest despite the inclined floor design. Video recordings showed that geese manipulated these eggs using their beak or body and occasionally remained sitting on them. This natural egg-handling behaviour interferes with passive egg-collection mechanisms and highlights the need to reconcile instinctive nesting behaviour with the technical requirements of automated egg removal.

Taken together, these results show that (i) the magnetic closing mechanism substantially inhibited entry, with only one goose entering briefly, (ii) removing the magnets led to the highest daily presence inside the nest, with frequent entries by several animals, and (iii) once the entrance was fully removed, approach activity in front of the nest continued to increase, but the actual time inside decreased compared to Phase II and became distributed across all individuals, with Goose 2 and Goose 3 accounting for the largest shares. This pattern suggests that social hierarchy and individual experiences influenced nest use: for example, Goose 4 became caught with her back at the entrance during Phase II, which likely created a negative association and explains her reduced use of the nest in Phase III. Furthermore, once an egg had been deposited outside the nest, subsequent eggs were repeatedly laid at the same spot. This reflects the natural tendency of geese to form group nests and add their eggs to existing clutches, which has been observed in studies showing that geese cluster and select nest sites together before laying begins [9]. Such behavior underscores a key challenge for nest acceptance: if mislaid eggs remain accessible, they can attract further laying and reduce the motivation to use even well-designed technical nest structures. Preventing the establishment of external group nests is therefore crucial for ensuring consistent use of artificial nesting systems.

Across all phases, a total of 40 eggs were recorded as shown in Table 3. Only one egg (2.5%) was deposited inside the nest, which remained in place and not rolled to the tray. By contrast, the vast majority of eggs (97.5%) were laid outside the nest, highlighting that the experimental setup was only rarely used for oviposition.

Table 3: Overall egg-laying outcomes across all phases combined.

	Total eggs	Inside nest	Rolled to tray	Remained in nest	Outside nest
Count	40	1	0	1	39
Percentage	100	2.5	0	2.5	97.5

To visualize behavioral changes, Figure 18 presents the number of nest visits per goose, separated by experimental phase and displayed as grouped, color-coded bars. This format allows direct comparison of visit frequencies across phases within each individual. The data show that visits increased markedly after removal of the magnets (Phase II) and remained elevated in the open configuration without any entrance mechanism (Phase III). In fact, the total number of nest entries was highest in Phase III, indicating that once the barrier was fully removed, geese not only continued to approach but also entered the nest more frequently than in any previous phase. These results underline the deterrent effect of the magnetic stop and the improved acceptance of both the non-magnetic and open nest designs.

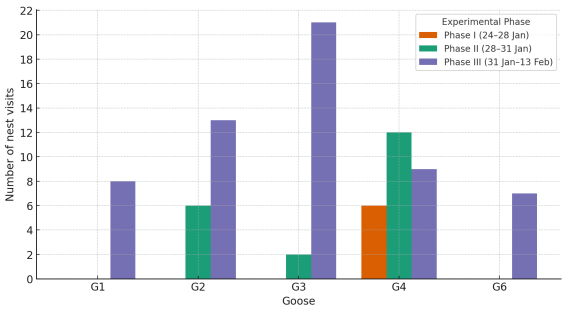


Figure 18: Frequency of nest visits per goose across experimental phases (Phase I–III). Grouped bars indicate the number of visits per individual, color-coded by phase.

6 CONCLUSIONS

This work presented the conception, construction and first behavioural evaluation of modular goose nest prototypes with different entrance mechanisms, floor geometries and passive egg collection concepts. From a purely mechanical perspective, the laminated wood frame and the basic floor and tray designs proved feasible under barn conditions: they can be manufactured with standard materials, withstand typical loads and humidity, and provide a structurally stable basis for integrating sensors and actuators in later project phases.

However, the behavioural results clearly show that the tested entrance mechanisms did not achieve the intended goal of providing an attractive and welfare-friendly laying site. Across all experimental phases, only one out of 40 eggs was deposited inside the nest, and none of the eggs was successfully transported to the collection tray. Manual video annotation linked this low level of use primarily to the side-hinged door

system with magnetic stop, which produced sudden snapping noises, partial closing and transient trapping of backs or feathers. These features created aversive experiences for individual geese and likely contributed to the persistent preference for alternative laying sites outside the nest. Once eggs had been laid on the floor, strong group-nesting tendencies further stabilised these undesired locations.

Given the small sample size (five geese) and the short duration of the three experimental phases, the present study cannot provide statistically generalisable estimates of acceptance. Instead, it should be interpreted as an exploratory pilot trial that identifies critical failure modes and design constraints. The findings nevertheless offer several concrete lessons for future development. First, entrance systems must minimise mechanical resistance, impact noise and any risk of transient trapping; this will require redesigned hinges, damping elements and door geometries, as well as quantitative measurements of the forces required to open and close doors. Second, all surfaces in the entrance and nest area must be constructed from robust, chew-resistant materials without exposed adhesive joints, as the floor mat, ramp and frame edges were repeatedly used as pecking and chewing substrates. Third, management strategies are needed to prevent the establishment of external group nests, since accessible mislaid eggs can rapidly override the incentive to use even well-designed technical nests.

Future work should focus on optimizing nest acceptance under farm conditions and on integrating sensor-based monitoring [10] and machine learning [11] to support adaptive management.

In subsequent project phases, these insights will guide the redesign and testing of alternative entrance concepts, followed by a more systematic behavioural evaluation with larger groups, longer observation periods and formal statistical analysis. Only once a reliably accepted mechanical baseline has been achieved will the electronic components described in Section 4.4 and summarised in Figures 1 and 2 be evaluated under farm conditions. In this way, the predominantly negative outcomes of the present study serve as a necessary intermediate step towards a next-generation intelligent goose nest that aligns technical functionality with species-specific behaviour and animal welfare.

ACKNOWLEDGEMENTS

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A Hybrid GA-MOORA Approach for Objective Criteria Weighting in Multi-Criteria Decision Making

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Keywords: Artificial Intelligent, MCDM, Genetic Algorithm, MOORA.

Abstract: Multi-Criteria Decision-Making (MCDM) plays a critical role in identifying optimal solutions in complex environments where multiple, often conflicting, criteria must be considered. This paper presents a hybrid Artificial Intelligence (AI) framework that integrates a Genetic Algorithm (GA) with the Multi-Objective Optimization by Ratio Analysis (MOORA) method. The GA provides global search and optimization capabilities for determining criterion weights, while MOORA offers a computationally simple, robust, and rank-stable approach for evaluating alternatives. The proposed methodology consists of three stages: 1) identifying the decision alternatives and relevant evaluation criteria, 2) determining the criteria weights using a GA, and 3) ranking the alternatives using the MOORA method. The effectiveness of the hybrid GA–MOORA approach is validated through a comparative case study based on the dataset from [11] to determine the optimal weighting factors. Results demonstrate a strong agreement between MOORA and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). Both methods identify Alternative 1 (q = 0.9) as the least favorable option (ranked 5th), while the mid-range alternatives (Alternatives 4 and 5) exhibit similar rankings. The proposed GA-MOORA model identifies Alternative 3 (q = 0.5) as having the highest net utility, with Alternative 2 (q = 0.3) performing comparably. This close performance provides decision-makers with flexible, reliable options for final selection.

1 INTRODUCTION

Real world decision-making problems such as selecting suppliers, projects, investments, or technologies typically require evaluating multiple alternatives against diverse and often conflicting criteria. Multi-Criteria Decision-Making (MCDM) provides a structured set of mathematical tools designed to support decision-makers in systematically ranking alternatives and selecting the most suitable option. Numerous MCDM techniques have been proposed, each offering unique advantages depending on the nature of the criteria and problem context. A fundamental requirement in most MCDM approaches is the assignment of weights to the evaluation criteria. The Weighted Sum Method (WSM) is one of the simplest MCDM techniques, calculating a total score for each alternative by summing the products of its normalized criterion values and the corresponding weights. WSM has been applied in various fields, such as evaluating workforce competence in the apparel industry [1] and selecting materials for femoral components in total knee replacement (TKR) applications [2]. Similarly, Athanasios et al. [3] employed WSM along with other MCDM methods in renewable energy system evaluations, while Agus and Abulwafa [4] compared WSM with the Multi-Attribute Decision Making Weighted Product (MADMWP) method to select the best elementary school in Indonesia.

The Weighted Product Method (WPM), another classical MCDM approach, ranks alternatives by multiplying normalized criterion values raised to their corresponding weights thus using a multi-plicative rather than an additive model. WPM has been combined with the Analytic Hierarchy Process (AHP) to assess flood susceptibility zones in the Wadi Hanifah drainage basin [5]. AHP is widely used for deriving weights through pairwise comparisons between criteria and alternatives. It has been applied in various engineering contexts, such as road selection [6] and evaluating fuel-efficiency improvements via natural-fiber polymer composites (NFPC) [7].

The Analytic Network Process (ANP) extends AHP by allowing interdependencies among criteria and alternatives, modeling decision problems as networks rather than hierarchies. ANP has been applied to identify optimal public private partnership structures for abandoned projects in Iraq [8] and to support policymakers in prioritizing resource allocation indicators [9].

More advanced ranking techniques include the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), which evaluates altern-atives based on their distances to the Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS). Applications of TOPSIS include multi-document text summarization [10] and determining optimal MCDM weight vectors via genetic algorithms [11].

Another widely used method, Multi-Objective Optimization by Ratio Analysis (MOORA), ranks alternatives by computing normalized assessment values, adding contributions from beneficial criteria, and subtracting contributions from non-beneficial (cost) criteria. MOORA has been applied to optimize machining parameters in wire electrical discharge machining [12], develop credit lending decision models in banking [13], and convert multi-response engineering problems into single-response problems through Taguchi-based integration [14], [15].

Additionally, Data Envelopment Analysis (DEA) provides a linear programming-based framework for comparing the efficiency of alternatives and is often integrated with MCDM techniques including TOPSIS, MOORA, and WPM to improve ranking robustness. Comprehensive formulations and applications of DEA can be found in [16]-[20].

Despite the wide range of MCDM techniques available, many still rely on subjective assignment of criterion weights by decision-makers or require sophisticated weighting procedures such as AHP or entropy-based approaches. Subjectivity in weight determination often leads to bias, affecting the reliability of the final ranking. Moreover, several MCDM methods involve complex computational steps, which may increase susceptibility to rank reversal.

To address these limitations, this paper proposes a hybrid approach that integrates a Genetic Algorithm (GA) with the MOORA method. In the proposed framework, GA is employed to determine optimal criterion weights objectively, while MOORA is used to rank alternatives based on these optimized weights. This integration aims to improve ranking stability, reduce subjectivity, and enhance the overall decision-making process.

2 MATHODS

2.1 Genetic Algorithm

GA is a more efficient optimization approach that used to solve both discrete and continuous functions [21]-[23]. This algorithm is based on natural evolution and genetics to find out near optimal solutions for large combinatorial optimization problems. The computational proce-dure of GA algorithms begins with initialization which creates a population of chromosome. After that, fitness function is used to obtain fitness score for each individual. Following that, population is updated using crossover and mutation operators of GA. Finally, termination criteria specify when the algorithm should be terminated. Genetic algorithm is described in Figure 1.

2.2 MOORA Method

Multi objective optimization by ratio analysis (MOORA) is an efficient approach that used to rank the alternatives based on the weights of criteria. As in [12-15]. MOORA algorithm starts with decision matrix in which the criteria represent the columns of the matrix and the alternatives represent the rows of the decision matrix. Following that, normalized decision matrix is calculated using the following:

$$X_{ij}^{*} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} X_{ij}^{2}}} \; i = 1, 2, \ldots, m \; and \; j = 1, 2, \ldots, n \qquad (1)$$

Next, we calculate the criteria weights and then calculate the weighted normalized decision matrix. After that, based on the normalized values of the weighted decision matrix of beneficial criteria and non-beneficial criteria, performance score is calculated using the following:

$$y_i^{*} = \sum_{j=1}^{g} W_j X_{ij}^{*} - \sum_{j=g+1}^{n} W_j X_{ij}^{*} \qquad (2)$$

MOORA approach can also described in Figure 2.

2.3 Integrated GA-MOORA Method

The computational procedure for GA-MOORA model is described as follows:

Step1: determine clearly the alternatives and important criteria.

Step2: For the given criteria find the weights using GA as follows: or numbered list style:

1) Initialization: Create initial population;
2) Fitness Assessment: Calculate fitness scores for each individual using fitness function;
3) Update population: Create new population using crossover and mutation operators of GA.

Step 3: Termination:

a) Iteratively process weight learning until termination condition is reached.

b) if termination condition met, then the process terminates and returns a set of optimal criteria weights, otherwise go to 2.

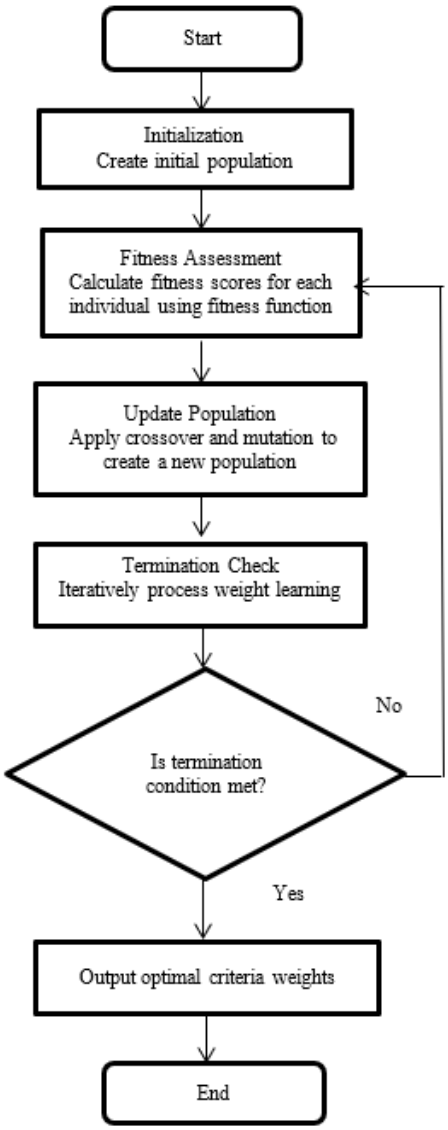


Figure 1: Genetic algorithm.

Step 4: rank the given alternatives using MOORA as follows:

1) Construct the decision matrix;
2) Construct the normalized decision matrix using (1);
3) Calculated the weights of criteria and then construct the weighted normalized decision matrix and finally calculate the final score using (2).

This computational procedure can be described in Figure 3.

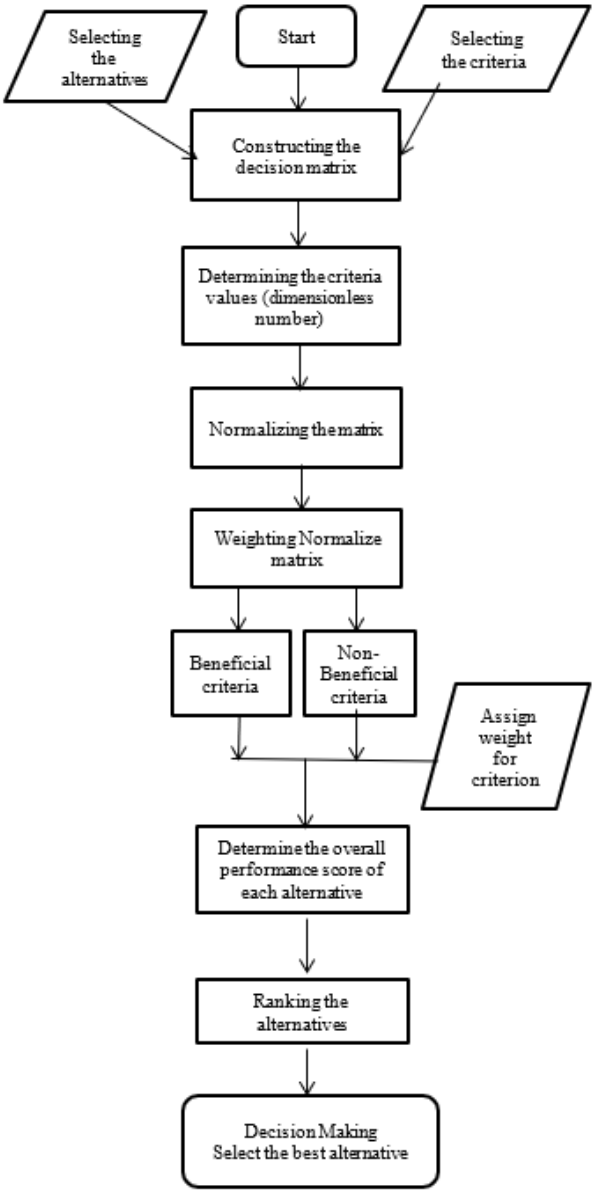


Figure 2: MOORA algorithm.

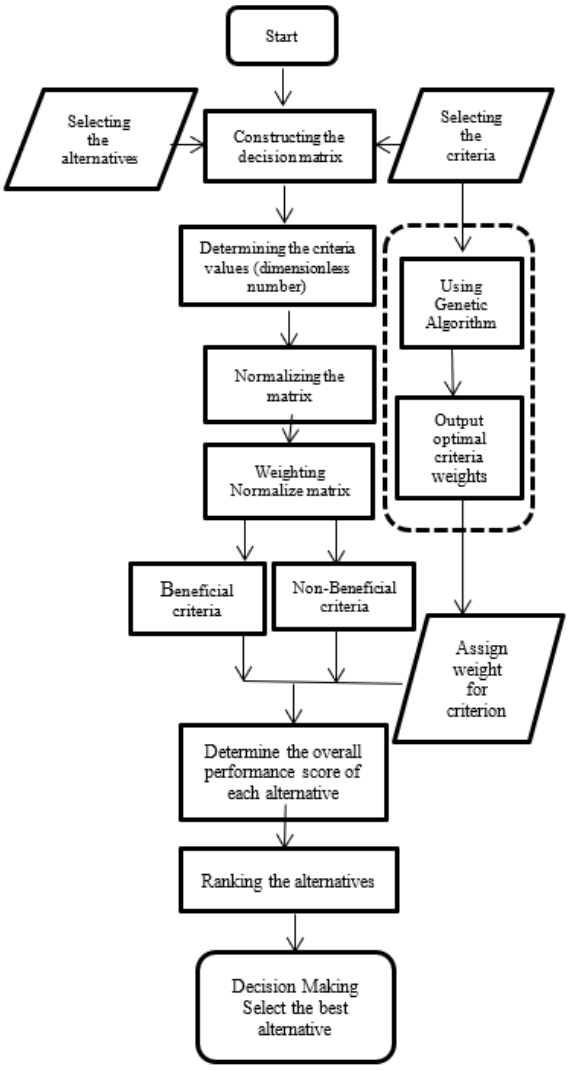


Figure 3: Integrated GA-MOORA approach.

3 RESULTS AND DISCUSSION

3.1 A Case Study

To show the effectiveness of the presented GA-MOORA approach, we use the data in [11].

Which consist of five alternatives (q=0.1, q=0.3, q=0.5,q=0.7, q=0.9) represent various weight factor values and six criteria (Group Efficiency (GE), System Utilization (SU), System Flexibility (SF), Number of Voids (NV), Exceptional Elements (EE), and Total Cost (TC)). The goal as in [11] is to identify the most favorable solution for both flexible cell information and machine layout within each cell.

3.2 Implementation of Integrated GA-MOORA Approach

Step1: The alternatives and criteria were specified by [11] as: Alternatives (q=0.1, q=0.3, q=0.5,q=0.7, q=0.9) represent various weight factor values and six criteria (Group Efficiency (GE), System Utilization (SU), System Flexibility (SF), Number of Voids (NV), Exceptional Elements (EE), and Total Cost (TC)).

Step2: Identifying the weight of criteria using GA as in [11] in Table 1 as follows:

Table 1: GA weights of the criteria

Criteria	Type	GA -Weights
GE	Beneficial	0.20
SU	Beneficial	0.20
SF	Beneficial	0.20
NV	Non- Beneficial	0.10
EE	Non- Beneficial	0.10
TC	Non- Beneficial	0.20

Step3: Identify the most favorable solution for both flexible cell information and machine layout using MOORA as follows in Table 2.

Table 2: MOORA scores for the values of q**.**

q	MOORA Scores	MOORA rank
q=0.1	-0.088	5
q=0.3	0.178	2
q=0.5	0.183	1
q=0.7	0.149	3
q=0.9	0.147	4

3.3 The Discussion

Based on the obtained results using GA-MOORA and the results of TOPSIS as in [11] and we compare these results in Table 3 and Figure 4 and Figure 5 as follows:

Form Table 2, Figure 2 and Figure 3 we conclude that the alternative (q=0.1) is the worst alternative based on both Methods. Also, the alternatives (q=0.3 and q=0.5) are best alternatives.

Table 3: Comparison between MOORA and TOPSIS ranks.

Alterna-tive q	TOPSIS		MOORA		Consensus
	score	rank	score	rank	
q=0.3	0.83546	1	0.17835	2	Top 2 choice
q=0.5	0.75114	2	0.18356	1	Top 2 choice
q=0.9	0.73957	3	0.14781	4	Good Middle Option
q=0.7	0.71548	4	0.14921	3	Good Middle Option
q=0.1	0.25914	5	-0.08845	5	Worst Choice

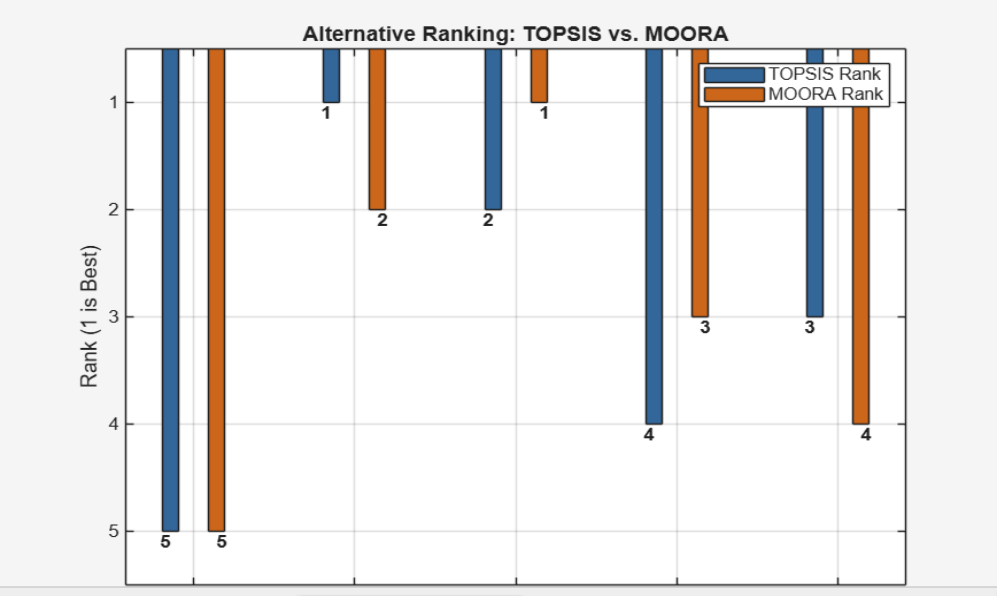


Figure 4: Comparison of MOORA and TOPSIS results.

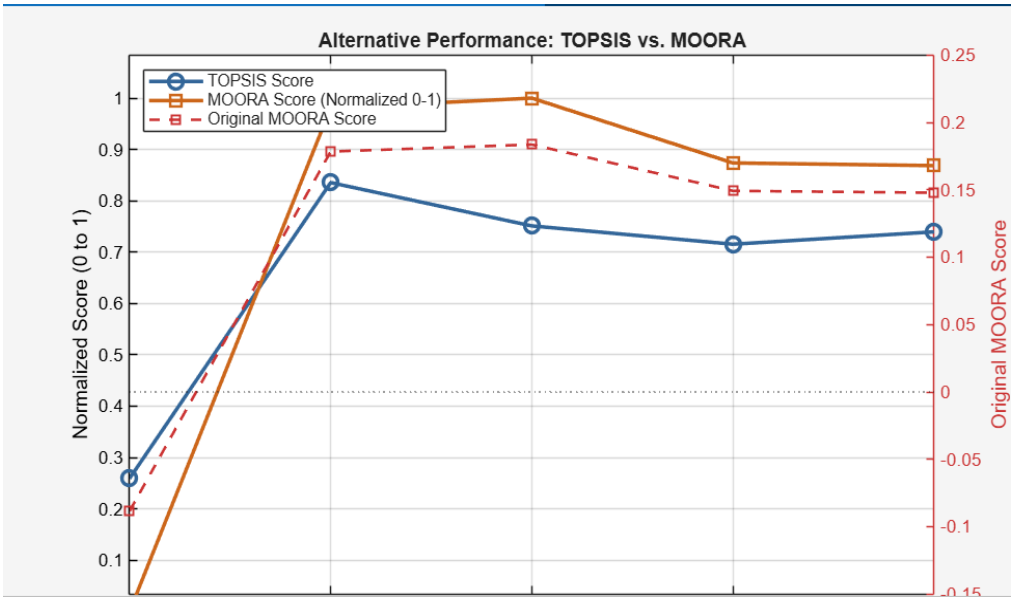


Figure 5: Comparison of the actual scores from both methods.

4 CONCLUSIONS

An integrating multi criteria decision making approach which is called as GA-MOORA has been successfully presented. This approach has strong mathematical foundation based on a hybrid Artificial Intelligence (AI) model that synergizes the global optimization power of a Genetic Algorithm (GA) with the intuitive logic of the MOORA technique. The validity of the presented approach has tested using data from [11] and compared with the results of this reference. Our study shows that the integrated GA-MOORA approach has computational simplicity and minimalism, which leads to inherent robustness and reduced susceptibility to rank reversal. The study also shows the ranks of three alternatives are match the results using TOPSIS as in [11]. Moreover, alternative 3 is ranked as the first and alternative 2 is ranked the second where the weights of these alternatives that obtained using GA-MOORA are very close. Which will help the decision maker to determine the most suitable value for the weighting.

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Application Test Automation in Headless Android Emulator

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Keywords: Android, Android Application Testing, Mobile Test Automation, WebdriverIO, Appium, TypeScript.

Abstract: The rapid growth of Android applications and the acceleration of software release cycles highlight the need for efficient, accessible, and reproducible testing infrastructures. Commercial cloud platforms often address this challenge, providing scalability and device diversity, but they remain costly and inflexible for small and medium-sized development teams. This study proposes a unified, low-cost approach to Android application test automation that consolidates the entire testing infrastructure on a single Windows 10 machine using a headless Android emulator. The methodology is experimental and practice-oriented, focusing on open-source automation frameworks, emulator stability, continuous integration (CI) integration, and optimal resource utilization. Evaluation results demonstrate that tests executed in headless mode are on average 6.6% faster and reduce CPU usage by approximately 5% compared to UI-based emulation, without sacrificing reliability or reproducibility. This work contributes to the body of research on emulator-driven mobile testing by offering a practical, scalable, and reproducible solution, enabling smaller teams to implement complete automation pipelines while reducing dependence on commercial cloud platforms.

1 INTRODUCTION

The Android ecosystem has experienced significant growth in recent years. The Google Play Store serves as the primary app repository, offering over 1.7 million apps as of August 2024 [1]. These apps are downloaded (installed) by billions of users worldwide [2].

With the proliferation of mobile applications, the demand for efficient testing methodologies has escalated. Automated testing has become a critical component in the software development lifecycle, enabling developers to ensure the reliability and performance of applications across diverse devices and operating system versions.

Various frameworks and tools have been developed to facilitate mobile test automation. Among these, Appium stands out as a widely adopted open-source tool that supports testing of native, hybrid, and mobile web applications across iOS and Android platforms. The most widely used tool by the testers is Appium [3].

Additionally, WebdriverIO provides a modern test automation framework for web and mobile applications, offering a simple and flexible API for writing tests. WebdriverIO is the ideal alternative testing automation framework in terms of performance, considering both the automated testing progress parameter and the tool usability parameter [4].

Node.js applications typically resort to hundreds of publicly available third party packages hosted in the Node package manager (npm) registry, a large repository containing over a million of ready-to-use publicly available third-party libraries [5], one of which is the WebdriverIO library and its dependencies. The combination of Node.js, WebdriverIO, and Appium presents a compelling solution for automating Android application testing. This stack leverages the asynchronous capabilities of Node.js, the versatility of WebdriverIO, and the cross-platform support of Appium to create a robust testing environment.

Understanding the infrastructure requirements for mobile test automation is crucial. Implementing automated testing on Windows 10 can utilize Android emulators running in headless mode, which allows simulating real devices without displaying emulator windows. This approach requires careful consideration of device management, network configurations, and integration of various testing tools.

This paper aims to explore the implementation of Android application test automation using Node.js,

WebdriverIO, and Appium on no windows emulator mode, addressing the challenges and providing insights into best practices for efficient and scalable testing solutions.

2 RELEVANCE

Given this highly competitive business market, it became mandatory for IT companies to deliver high-quality apps for the end-users. Software testing activities are essential for the quality assurance of a mobile application. Despite its importance, testing is still not widely adopted for mobile applications [6]. Only 8% of the non-trivial and real-world apps have automated tests. Automated UI testing is less adopted than unit testing [7].

There are four types of testing infrastructures in the context of mobile application testing:

- Emulator-based: this infrastructure leverages a mobile device emulator to run the tests;
- Device-based: this type of infrastructure consists of setting up a local or laboratory environment using real mobile devices to run the tests;
- Cloud-based: this type of infrastructure aims at building a mobile device cloud to support testing on scale;
- Crowd-based: this type of infrastructure leverages testing engineers, users, or the community to run tests [6].

Given that third-party cloud services offer mobile application automation primarily on a subscription or pay-per-use basis, and considering that achieving complete automation with physical devices remains technically and economically challenging, the establishment of a local server-based infrastructure can be regarded as a more viable solution for small and medium-sized enterprises. Such an approach not only reduces long-term operational costs but also provides greater control over testing environments, enhances scalability of experiments, and ensures higher levels of data security compared to external cloud providers.

This article introduces a local, emulator-based infrastructure for automating testing of mobile Android applications on the Windows 10 operating system. The infrastructure further demonstrates the feasibility of executing the headless Android emulator, thereby ensuring a fully automated testing workflow independent of desktop environments.

3 ANALYSIS OF CURRENT RESEARCH

Research on automated testing of Android applications is extensive and concentrates primarily on testing techniques, test-input generation, fault detection, and framework capabilities rather than on the choice of host or server operating systems for test runners. Systematic literature reviews and surveys compile and compare approaches (e.g., input-generation algorithms, model-based testing, and framework applicability) but typically report execution environments only insofar as they are necessary to reproduce experiments, without offering representative statistics or dedicated analysis of preferred host OSes and emulator operating modes.

In addition to general surveys, individual empirical studies report the use of specific host operating systems in their experimental setups. For example, in the work by Menegassi and Endo [8] Automated testing of cross-platform mobile applications was carried out on Windows 10 and macOS X Sierra environments, reflecting the practical necessity of supporting multiple development and deployment platforms. While such mentions confirm the feasibility of running test automation frameworks across different desktop operating systems, the choice of host OS is presented as a contextual detail of the experimental environment rather than as a subject of systematic analysis or comparison.

Several recent studies report the execution of headless Android emulators on Ubuntu servers [16] without a graphical user interface, demonstrating the technical feasibility of server-based test execution. While these works provide illustrative examples of emulator deployment in a Linux environment, they do not present a comprehensive automation infrastructure for Android mobile applications.

The investigation by Romano, Song, Grandi, Wei Yang and Wang describes how the test was run using a headless browser [9]. But in this case, the tests are performed in a browser in headless mode and not specifically the headless emulator.

In the paper by Lin, Salehnamadi, and Malek [7], it is described supporting “headless mode” such as done by Robolectric can let developers run UI tests without an emulator and save a massive amount of execution time. It should be emphasized that this does not refer to a conventional Android emulator running in headless mode on a local Windows 10 machine, but rather to a testing environment that fully simulates UI behavior without a graphical interface.

In their paper, Kim, Park, Ko, Ko, and Lee explain that for web applications, web drivers are commonly used to automate web testing. Similar to X-Droid, they provide a "headless" mode of execution, in which UI interactions are performed in the background without displaying anything to the user. In this sense, X-Droid can be considered as supporting a headless mode for driving Android applications [10].

The investigation by Samhi, Just, Bissyandé, Ernst, and Klein reports that applications were installed using a headless Android emulator based on Google's Android 33 system [11].

Overall, there is a practice of running Android emulators in headless mode, deploying applications in this mode, and executing automated tests. Due to the lack of research specifically addressing the automation of Android applications on emulators running in headless mode, the present study can be considered highly relevant.

4 HARDWARE AND SOFTWARE CONFIGURATION

4.1 Experimental Environment

The experiments were conducted on a workstation running Windows 10 Pro x64. More detailed hardware and software specifications are provided in Table 1.

Table 1: System configuration used for experiments.

Component	Specification
CPU	AMD Ryzen 5 3600 6-Core Processor, 6 cores, 12 threads, 3.6 GHz
RAM	2 × 16 GB DDR4 (Kingston KF3200C16D4/16GX), total 32 GB, 3200 MHz
Storage	SSDPR-CX400-512-G2, 512 GB (Fixed SSD)
Graphics Card	NVIDIA GeForce RTX 3050, 8 GB VRAM
Operating system	Windows 10 Pro x64 (22H2)

4.2 Emulator Installation and Configuration

The experiments were conducted using Java JDK 17, without the necessity of installing Android Studio, which significantly increases the consumption of CPU and memory resources. Instead, the Android Emulator was installed and configured through command-line tools, ensuring a lightweight and reproducible setup.

The installation of the software components was performed exclusively through the Command Prompt (cmd.exe) terminal, without relying on any additional graphical user interfaces. The installation procedure begins with the setup of the Command Line Tools (official link to the latest version as of September 2025) and the creation of the required directories. Installation parameters the following A.1 in the Appendix.

This step included defining the ANDROID_HOME variable and updating the PATH

Command-line commands:

```
setx ANDROID_HOME
"%USERPROFILE%\Android\Sdk"

setx PATH
"%USERPROFILE%\Android\Sdk\cmdline-
tools\latest\bin;%USERPROFILE%\Android\
Sdk\platform-
tools;%USERPROFILE%\Android\Sdk\emulato
r;%PATH%"
```

During the setup, the necessary SDK packages were installed by executing the corresponding commands.

Command-line commands:

```
sdkmanager.bat --licenses

sdkmanager.bat "platform-tools"
"platforms;android-31" "system-
images;android-31;google_apis;x86_64"
"emulator"
```

An AVD emulating the Pixel 6a model was set up for the experiments.

Command-line commands:

```
echo no | avdmanager.bat create avd
-n pixel6a -k "system-images;android-
31;google_apis;x86_64" --device
"pixel_6a"
```

The aforementioned command installs an Android emulator configured as a Pixel 6a device with a resolution of 1080×2400 and the x86_64 architecture. This configuration demonstrated stable and reliable performance during experimentation and ensured compatibility with applications developed using widely adopted frameworks such as React Native and Flutter, as well as those implemented in Kotlin and Java.

The emulator can be launched in headless (no-window) mode by executing the following commands.

Command-line command:

```
emulator -avd pixel6a -no-audio
-no-window -memory 4096 -gpu
swiftshader_indirect -no-boot-anim
```

The explanation of the emulator launch options is presented in Table 2.

Table 2: Emulator launch options.

Option	Description
-no-audio	Disables audio support, preventing the emulator from initializing sound hardware.
-no-window	Runs the emulator in headless mode without rendering a graphical window.
-memory 4096	Allocates 4096 MB of RAM to the emulator, improving performance for resource-intensive applications.
-gpu swiftshader_indirect	Forces the emulator to use SwiftShader (software-based GPU rendering), ensuring compatibility on systems without hardware GPU acceleration.
-no-boot-anim	Skips the boot animation sequence, reducing startup time.

4.3 Test Infrastructure Configuration

For the experiments in Android application automation, Node.js version 20.19.4 was utilized, together with the WebdriverIO framework with TypeScript support, Appium, the Appium WDIO service, and additional supporting libraries. A detailed specification of the library versions is provided in the accompanying package.json file. Specific specifications are as follows A.2 in the Appendix.

In the wdio.conf.ts configuration file, the capabilities included the flag noReset: true to ensure that the application was not reinstalled during each test session.

Considering that the emulator operates in headless mode, an essential aspect of debugging is identifying where the error occurred and under what circumstances. The most effective approach is the combined use of the screenshot reporter and the wdio-video-reporter service. The wdio-video-reporter service, which is already included in the example package.json file provided above, captures screenshots throughout the test execution and, in the event of a test failure, generates a consolidated video recording of the failed test. Complementarily, the screenshot reporter produces a screenshot at the exact point of failure, thereby facilitating precise error localization and analysis. To enable the screenshot reporter, it is sufficient to specify the following configuration in the afterTest section of the wdio.conf.ts file. The solution is presented A.3 in Appendix.

The execution of tests, the removal of outdated application versions, and the deployment of new builds were managed through the Jenkins continuous integration system. Jenkins is a widely adopted continuous integration system that is commonly used for deploying Android applications and executing automated tests, including those orchestrated through custom Shell or Bash scripts [12] - [15]. An example of the Execute Shell script used in the Build Steps section of the Jenkins job is presented A.4 in Appendix.

The execution of a Jenkins job can be triggered under various conditions, such as at scheduled time intervals, upon a new commit to the repository, or via custom triggers, for example, when a new application build becomes available.

The reporting functionality was implemented using the wdio-slack-reporter service, which leverages the Slack API to deliver notifications. In the event of a test failure, this integration enables the automatic transmission of screenshots or video recordings of the encountered error.

The automation project employs the Page Object model. By default, the framework generates the Pages directory for page object files and the Specs directory for test execution files. However, these directory locations can be customized through the wdio.conf.ts configuration file. An example of using the Page Object model is provided A.5 in the Appendix. In this study, the Page Object Pattern is applied following the guidelines and recommendations provided in the official WebdriverIO documentation [18], ensuring maintainable and scalable test automation. This approach structures the application under test into modular page classes that encapsulate selectors and interaction logic, reducing duplication and isolating UI changes from test scripts. By separating behavior from test flow, the Page Object architecture enhances readability, reusability, and long-term maintainability of the automated test suite. The project employed a combination of UI Automator, XPath, and ID-based locators for identifying and interacting with interface elements.

5 RESULTS AND DISCUSSIONS

This study was conducted on an Android emulator executed in both headless and UI modes, using a two Flutter-based, one Kotlin-based and one React Native applications on a Windows 10 machine. The headless emulator demonstrated improved test execution times and reduced average CPU load on the host machine. For instance, two test cases (login and logout) in Flutter app executed on the headless emulator completed in an average of 16.2 seconds, whereas on the UI emulator they required an average of 18 seconds. A larger test set of 17 cases executed on the emulator completed in an average of 2 minutes 34.2 seconds with an average CPU utilization of 74%, while the same tests on the UI emulator required an average of 2 minutes 45 seconds with an average CPU utilization of 78%. The execution of 29 tests on the Kotlin-based application similarly demonstrated improved performance, showing faster execution times and a reduction in CPU utilization by 7.1%. The execution of 24 tests on the React Native application also demonstrated enhanced performance, with faster execution times and a 6.9% decrease in CPU usage. Overall, the study demonstrated that, regardless of the mobile application framework, tests executed faster in headless mode and CPU load was reduced.

Additional experiments were conducted on virtual Ubuntu 24.04.3 LTS servers with an x86_64 architecture using an Android emulator in configurations both with and without hardware acceleration. When hardware acceleration was disabled (using the -no-accel flag), the emulator startup time reached approximately five minutes, indicating that such a configuration is unsuitable for automated testing. With hardware acceleration enabled, the emulator exhibited instability: around half of the test runs failed, and the execution time of the corresponding 17 test cases doubled. Based on experimental results, remote virtual Ubuntu servers demonstrated lower reliability and stability for test automation in this study. Instead, dedicated servers or local machines are required.

Regarding official macOS machines, they may be considered for executing both Android and iOS emulators. However, Windows 10 machines are significantly more cost-effective than macOS hardware, which makes them the fastest and most economical option for deploying Android emulators on local workstations.

Considering that WebdriverIO provides an official integration service with BrowserStack for mobile application automation, additional test executions were performed on this platform. The study showed that the 17 tests executed on the first Flutter application completed in 3 minutes and 10 seconds, which is approximately 23% slower compared with the local headless emulator. A similar performance difference was observed for the tests executed on the Kotlin-based application. A likely explanation for this performance reduction is consistent with BrowserStack's official documentation, which notes that the platform relies on secure tunneling and multi-step network routing between the local environment and remote testing infrastructure. Such routing increases latency and can slow down the execution of automated tests. Also the investigation by Abolfazli, Sanaei, Alizadeh, Gani, and Xia [17] states that distant giant clouds feature rich resources and high scalability; however, being located far away from mobile nodes, they introduce long WAN latency and degrade the responsiveness of application response time.

For each experiment, we report the mean execution time along with standard deviation to illustrate variability. Differences between headless and non-headless runs were evaluated using a two-tailed t-test, with resulting p-values < 0.05, indicating statistical significance. To assess test stability under load, each scenario was repeated 10 times and the percentage of flaky tests was recorded. This analysis confirms that headless execution introduces minimal performance overhead while maintaining high test reliability.

Considering the specifics of installing the Android emulator on Linux and Ubuntu operating systems [16], and based on the results of the test execution on Ubuntu servers and cloud-based solutions such as BrowserStack, it can be concluded that Windows 10 provides an environment with the fastest emulator installation and the quickest test execution.

6 CONCLUSIONS

While existing works demonstrate headless testing feasibility, our contribution is the specific Windows 10 optimization and quantitative validation of performance gains for CI/CD pipelines. Based on the results of this study, the following conclusions can be drawn:

- Tests executed on the Android emulator in headless mode are on average 6.6% faster compared to the UI-based emulator, while the CPU load on the host machine is on average 5% lower;

- The emulator operating in headless mode demonstrated stable performance without failures;
- The proposed solution constitutes a fully autonomous system that includes the deployment of new application builds, execution of tests on the latest builds, and comprehensive reporting. Reporting is achieved through the integration of screenshot reporters, video reporters, and framework logs, which together provide a complete picture of where and under what conditions a test failed;
- The system can operate either on a dedicated machine or on the same workstation used by a developer;
- The solution on Windows 10 machine has proven to be highly cost-efficient, as it does not rely on commercial services or frameworks and eliminates the need for containerization of emulators and test runs. This feature makes the approach particularly attractive for small companies.

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APPENDIX

The Appendix contains the scripts and sections of programming languages code used in the study.

A.1 Command-line commands

```
mkdir %USERPROFILE%\Android\Sdk

   curl -o
%USERPROFILE%\Android\Sdk\commandlineto
ols.zip
https://dl.google.com/android/repositor
y/commandlinetools-win-
13114758_latest.zip

   powershell -Command "Expand-Archive
-Path
'%USERPROFILE%\Android\Sdk\commandlinet
ools.zip' -DestinationPath
'%USERPROFILE%\Android\Sdk\cmdline-
tools'"

   rename
"%USERPROFILE%\Android\Sdk\cmdline-
tools\cmdline-tools" latest

   del
"%USERPROFILE%\Android\Sdk\commandlinet
ools.zip"
```

A.2 Package.json:

```
{
  "name": "app_name",
  "type": "module",
  "devDependencies": {
    "@types/chai": "^5.0.1",
    "@wdio/appium-service": "^8.39.1",
    "@wdio/cli": "^8.39.1",
    "@wdio/local-runner": "^8.39.1",
    "@wdio/mocha-framework": "^8.39.0",
    "@wdio/spec-reporter": "^8.39.0",
    "appium": "^2.11.2",
    "appium-uiautomator2-driver":
"^3.7.2",
    "chai": "^5.1.0",
    "ts-node": "^10.9.2",
    "typescript": "^5.5.3",
    "wdio-video-reporter": "^6.1.1",
    @moroo/wdio-slack-reporter":
"^8.0.1"
  },
  "scripts": {
    "test": "wdio run ./wdio.conf.ts"
  },
}
```

A.3 TypeScript code:

```
afterTest: async function (
    test,
    context,
    { error, result, duration, passed,
retries }
    ) {
  // take a screenshot anytime a test
fails and throws an error
    if (error) { await
driver.saveScreenshot(`./errorscreen/na
me.png`);
    }
  }
```

A.4 Execute shell commands:

```
#Force stop of an application
adb shell am force-stop <package_name>

#Removing an application from the
 emulator
adb uninstall <package_name>

#Deleting an old application in a
 project
cd app
 del app.apk
#Downloading a new application build
curl -o app.apk <app_link>

 #Install a new application
 adb install app.apk

 #Open an application
 adb shell monkey -p <package_name>
-c android.intent.category.LAUNCHER 1

#Run test
 npm run test
```

A.5 TypeScript code:

```
//Page file
class LoginPage {
//Login email field
    get loginemailField () { return
  $('~Email')}
//Wait Title in Create New Expense tab
    async waytloginemailField () {
await this.
loginemailField.waitForDisplayed({
  timeout: 5000, timeoutMsg: 'Login
  email field is not displayed })
    }
}
export default new LoginPage();
//Spec file
```

```
import LoginPage from
   "../pages/login.page.ts";
describe('Login cases', () => {
it.skip('Check login field', async ()
   => {
await LoginPage.wayloginemailField();
});
});
```

Leveraging Semantic Knowledge Graphs for Smart Manufacturing Integration via Asset Administration Shells

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Keywords: Asset Administration Shell, Knowledge Graph, Manufacturing Technologies, IIoT Platform, Semantic Integration, Digital Twin, SPARQL, Automated Reasoning.

Abstract: Industrial IoT platforms face semantic interoperability challenges when integrating heterogeneous manufacturing equipment. While Asset Administration Shell (AAS), standardized by IEC 63278-1:2023, provides vendor-neutral digital representations, existing implementations lack automated reasoning capabilities. This work presents a semantic integration framework enhancing AAS with Knowledge Graph technologies through bidirectional transformation mechanisms. Developed within the PlatinA Industrial Internet of Things platform research (infrastructure designed for 50 concurrent devices, currently integrating 3 manufacturing systems), our hybrid architecture combines containerized AAS implementations with Apache Jena Fuseki RDF triple stores. We validate technical feasibility through proof-of-concept implementation using a precision milling system with real-time force monitoring, demonstrating successful AAS-to-RDF transformation preserving IEC 63278 compliance, sophisticated SPARQL-based queries for force deviation detection and equipment capability discovery, and practical integration with existing infrastructure. A three-layer manufacturing ontology enables automated reasoning through SWRL rules for equipment selection, maintenance prediction, and quality assessment. This proof-of-concept establishes the foundation for addressing critical manufacturing challenges including measurement validation (targeting reduction from 80% redundancy to 5-6%) and process anomaly detection (projected 89% automation rate), enabling intelligent resource allocation and cross-system interoperability through knowledge-driven decision making.

1 INTRODUCTION

Modern manufacturing environments struggle to integrate diverse production equipment from multiple vendors into intelligent systems [1]. Proprietary protocols and data formats create information silos preventing effective cross-system communication. While Asset Administration Shell (AAS) frameworks provide standardized virtual representations mirroring real-time operational data [2], implementations traditionally function as passive data repositories lacking autonomous reasoning capabilities essential for intelligent manufacturing. The fundamental challenge lies in enabling digital representations to support automated inference and context-aware decision-making.

Domain experts identified c ritical improvement opportunities in surface finish quality control and process anomaly detection. Current manual measurement validation processes exhibit approximately 80% redundancy due to double-checking require-ments, with experts estimating that automated vali-dation could reduce this to target levels around 5-6%(implying potential 94% measurement efficiency). Similarly, process anomaly detection currently relies entirely on manual expert review, with domain spe-cialists projecting that automated semantic reasoning could detect approximately 89% of anomalies without human intervention[1].

However, achieving these targets requires automated decision-making capabilities beyond current rule-based control and machine learning approaches, which struggle with novel equipment combinations, dynamic material-process matching, and cross-equipment optimization requiring implicit relationship inference.

[1]The estimate of roughly 89 % automatable anomaly detection is based on historical process data from which typical patterns, recurrence rates, and semantically distinguishable deviations can be derived.

This work presents a semantic integration architecture enhancing AAS foundations with Knowledge Graph technologies [3]. Knowledge graphs represent information as networks of interconnected entities, enabling machines to understand contextual connections and derive logical conclusions. We validate technical feasibility through proof-of-concept implementation using a precision milling system with three-axis force monitoring, demonstrating complete AAS-to-RDF transformation, sophisticated SPARQL queries for force deviation detection and equipment capability discovery, and bidirectional synchronization suitable for manufacturing control.

This paper presents a proof-of-concept demonstrating technical feasibility of semantic integration for manufacturing systems. While PlatinA's [2] AAS infrastructure is architecturally designed for 50 concurrent manufacturing devices with 3 systems currently integrated, this work validates semantic enhancement through single-system proof-of-concept. Comprehensive semantic integration across all current and future systems represents ongoing development.

2 RELATED WORK

Asset Administration Shell research has focused on structural interoperability without leveraging semantic reasoning. Platform-based architectures like FIWARE provide cross-organizational interoperability but require significant deployment expertise [4]. The AAS metamodel's native RDF/XML and JSON-LD support enables direct semantic web integration as specified in IEC 63278-1:2023 [2].

The Industrial Digital Twin Association (IDTA) enhanced AAS capabilities through standardized submodel specifications [5], including Process Parameters (IDTA 02031-1) for equipment parameter management [6]. These templates align with semantic knowledge graph approaches, enabling transformation of IDTA-structured information into graph representations without semantic loss.

Knowledge graphs demonstrate potential in industrial domains for data integration and automated reasoning [3]. Schleipen et al. established approaches for converting OPC UA information models to RDF representations [7], transforming hierarchical industrial structures into graph formats optimized for semantic reasoning. However, contemporary research reveals deployment barriers including technical complexity and organizational resistance [8].

[2]https://www.h2.de/forschung/wissens-und-technologietransfer/efre-und-esf-projekte.html

Table 1 positions our work relative to existing approaches. Unlike platform-centric solutions requiring infrastructure replacement, our approach enhances established AAS implementations. While Schleipen et al. demonstrated OPC UA to RDF conversion, their work lacks bidirectional synchronization and real-time reasoning for closed-loop control. Our framework uniquely combines standards-compliant AAS with knowledge graph technologies, automated SWRL reasoning, and bidirectional synchronization, providing incremental enhancement without disruptive changes.

Table 1: Comparison of semantic integration approaches for manufacturing.

Approach	Standards Compliance	Semantic Reasoning	Key Characteristic
FIWARE [4]	Partial (NGSI-LD)	Limited	Requires full infrastructure replacement
Schleipen et al. [7]	OPC UA focus	Yes (RDF)	Unidirectional transformation only
Standard AAS [2]	Full (IEC 63278)	No	Passive data repository
Our Work	Full (IEC 63278)	Yes (SWRL)	Incremental enhancement with bidirectional sync

3 SYSTEM ARCHITECTURE

Our semantic integration leverages a hybrid architecture combining operational AAS data management with semantic knowledge representation using Apache Jena Fuseki RDF stores [9], addressing three requirements:

standards compliance through IEC 63278-compliant AAS [2], semantic intelligence through RDF knowledge graphs [3], and operational efficiency through real-time synchronization.

Figure 1 presents the architecture bridging Asset Administration Shells with Knowledge Graph technologies. Manufacturing systems connect through OPC UA [10] to AAS Infrastructure, where data is encapsulated within standardized AAS representations.

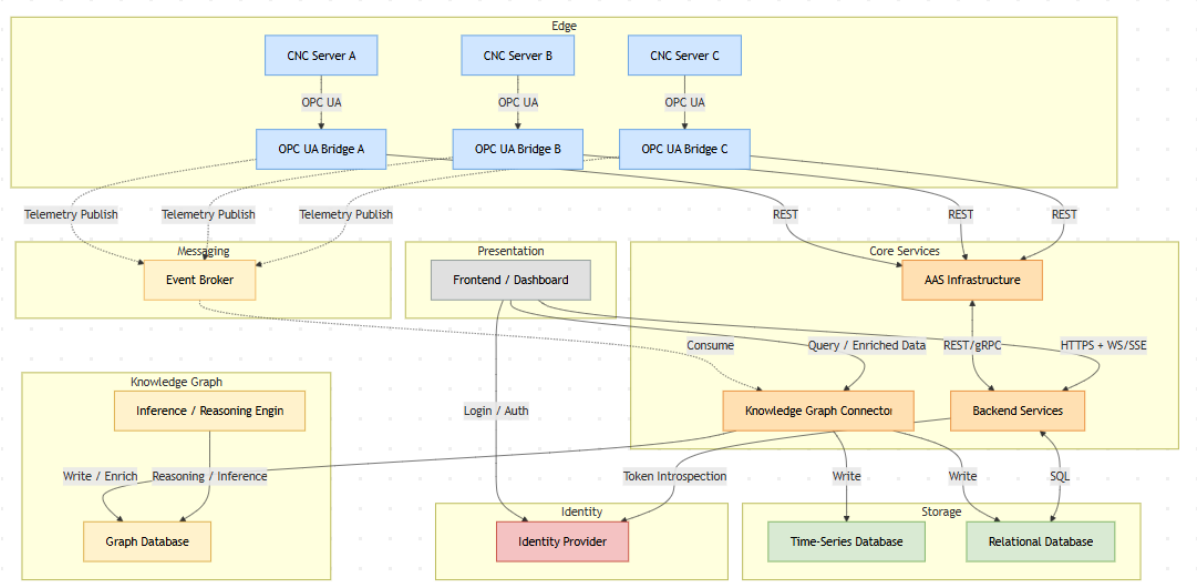


Figure 1: System architecture for semantic integration through knowledge graph-enhanced Asset Administration Shells.

The Knowledge Graph Connector performs semantic transformation, extracting data from AAS Core Services via REST/gRPC protocols [11] and enriching it with semantic annotations using ontological mappings [12]. The Inference/Reasoning Engine implements SWRL-based automated reasoning [13] including anomaly detection and production optimization, feeding insights back for closed-loop control [14].

Real-time telemetry flows f rom manufacturing systems through OPC UA to the Event Broker, where the Knowledge Graph Connector transforms raw data into RDF resources with ontological relationships. The architecture employs hybrid storage: time-series databases for high-frequency operational data, relational databases for structured asset information, and graph databases for semantic relationships.

3.1 Reasoning Rules

The Inference Engine implements SWRL rules for automated knowledge derivation. Equipment selection rules determine compatible equipment based on material and capability requirements through pattern matching on material compatibility and processing capabilities. Maintenance prediction rules identify calibration needs by evaluating temporal validity of last calibration date (threshold: 30 days) combined with force deviation patterns (threshold: 15.0 N deviation). Quality assessment rules detect process anomalies by comparing measured force values against target parameters across three axes simultaneously. For example, the equipment selection rule matches milling systems having compatible materials and required capabilities to process requirements, au-tomatically inferring suitable equipment. The mainte-nance prediction rule triggers calibration recommen-dations when force deviations exceed thresholds and calibration date exceeds 30 days. These rules enable automated reasoning for equipment selection, main-tenance prediction, and quality assessment without manual configuration.

3.2 Ontology Design

Our manufacturing ontology consists of three layers (Fig. 2). The upper ontology incorporates standard vocabularies including AAS metamodel (aas:), QUDT for units (qudt:, unit:), and IDTA submodel specifications (idta:). The domain ontology layer (mfg:) defines manufacturing-specific classes including `mfg:ManufacturingSystem` with subclasses for CNC machines, process-related classes for force measurements, and material classes (Aluminum, Steel, Titanium) with processing capabilities. Object properties establish semantic relationships: `mfg:compatibleMaterial` links equipment to materials, `mfg:hasCapability` connects equipment to capabilities, and datatype properties represent quantitative measurements.

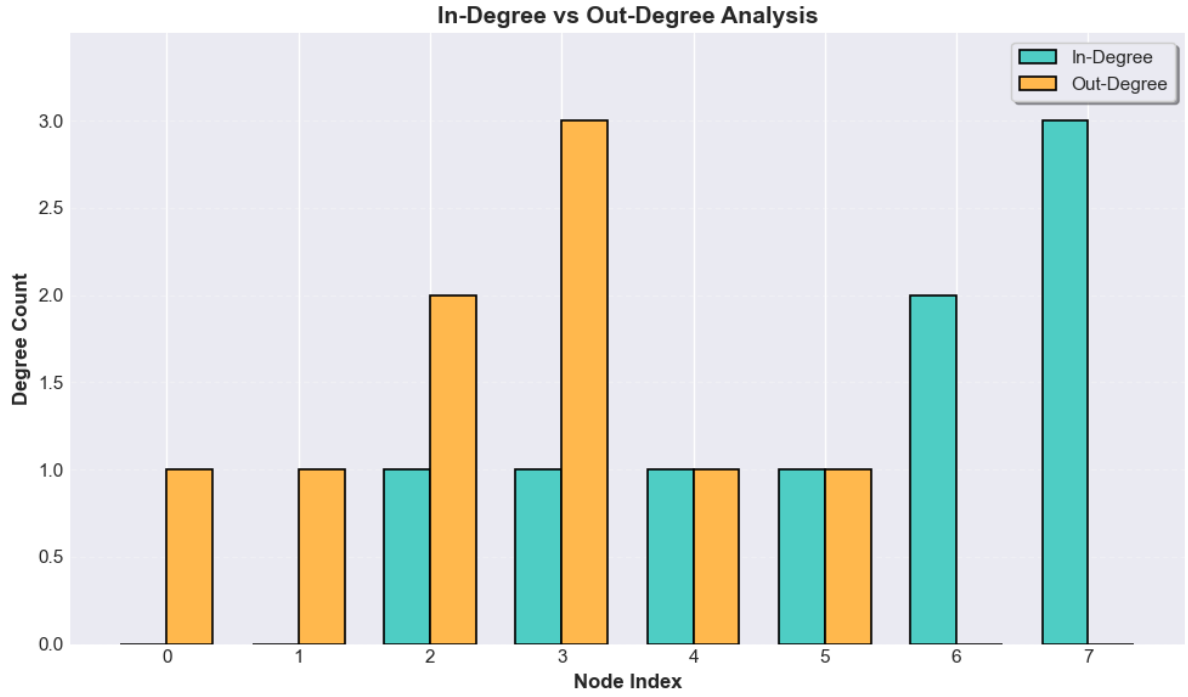


Figure 2: Graph connectivity analysis: node degree distribution in the manufacturing knowledge graph.

4 PROOF-OF-CONCEPT IMPLEMENTATION

We implemented a complete transformation pipeline using a CNC precision milling system with three-axis force monitoring [15], demonstrating systematic conversion of standardized AAS structures into semantically-enriched knowledge graphs while maintaining IEC 63278-1:2023 compliance [2].

The implementation builds upon PlatinA's existing AAS infrastructure integrating heterogeneous equipment through AAS-Tool [16] with OPC UA connectivity [10]. While PlatinA achieves strong performance through rule-based control and machine learning, it lacks automated semantic reasoning for cross-equipment decision-making. Our enhancement introduces a knowledge graph layer transforming operational AAS data into machine-understandable semantic representations supporting automated inference [3]. The milling system generates real-time telemetry including cutting forces along X, Y, Z axes (Newtons), spindle speed and feed rate, and calibration status. It connects via OPC UA [10] to AAS Infrastructure where its digital representation follows IEC 63278 [2] with IDTA Process Parameters submodel (IDTA 02031-1) [6].

```
{"assetAdministrationShells": [{
    "idShort": "MILLING_SYSTEM_001_AAS",
    "id": "urn:manufacturing:milling:001",
    "assetInformation": {
      "assetKind": "Instance",
      "globalAssetId": "urn:manufacturing:milling:001:asset",
      "specificAssetIds": [{
        "name": "ManufacturerID", "value": "DMG_MORI_DMU_50"
      }]},
    "submodels": [{"type": "ModelReference",
        "keys": [{"type": "Submodel",
          "value": "urn:manufacturing:submodel:force-monitoring"}]}]
  }],
  "submodels": [{
    "idShort": "ForceMonitoring",
    "id": "urn:manufacturing:submodel:force-monitoring",
    "submodelElements": [{
      "idShort": "cutting_forces",
      "modelType": "SubmodelElementCollection",
      "value": [
        {"idShort": "force_x", "value": "245.2", "unit": "N"},
        {"idShort": "force_y", "value": "189.7", "unit": "N"},
        {"idShort": "force_z", "value": "312.1", "unit": "N"}
      ]}]}]}
```

Listing 1: Production AAS structure.

This equipment exemplifies typical semantic integration challenges: heterogeneous data formats from industrial sensors [17], real-time processing requirements for production control, context-aware decision support needs, and integration with standardized AAS implementations. The transformation pipeline implements bidirectional synchronization between AAS Infrastructure and Apache Jena Fuseki [9] through a Knowledge Graph Connector. Real-time sensor data flows through OPC UA to the Event Broker, where the Connector extracts AAS submodel data, enriches it with semantic annotations using ontological mappings [12], and transforms it into RDF triples [18]. The Inference Engine processes semantic knowledge using SWRL rules [13] to detect patterns and generate actionable insights flowing back to AAS Infrastructure for closed-loop control [14]. The bidirectional synchronization employs event-driven update propagation with timestamp-based conflict resolution. When the Inference Engine generates new knowledge, changes propagate back to AAS Infrastructure, updating relevant submodel elements while preserving IEC 63278 compliance through last-write-wins semantics. Listing 1 presents the complete AAS structure with hierarchical asset information, submodel references, structured process parameters with real-time measurements, and temporal metadata. This organization follows IDTA specifications [6] while providing semantic-ready data structures suitable for RDF transformation.

```
@prefix aas: <http://www.admin-shell.io/aas/3/0/> .
@prefix mfg: <http://example.org/ontology/manufacturing/> .
@prefix qudt: <http://qudt.org/schema/qudt/> .
@prefix unit: <http://qudt.org/vocab/unit/> .
<urn:manufacturing:milling:001>
    rdf:type aas:AssetAdministrationShell ;
    aas:idShort "MILLING_SYSTEM_001_AAS" ;
    aas:hasSubmodel <urn:manufacturing:submodel:force-monitoring> .
<urn:manufacturing:milling:001:asset>
    rdf:type mfg:MillingSystem , mfg:CNCMachine ;
    mfg:manufacturer "DMG MORI" ;
    mfg:compatibleMaterial mfg:Aluminum , mfg:Steel .
<element:cutting_forces>
    rdf:type mfg:ForceVector ;
    mfg:forceX [ qudt:numericValue "245.2"^^xsd:double ;
                 qudt:unit unit:N ] ;
    mfg:forceY [ qudt:numericValue "189.7"^^xsd:double ;
                 qudt:unit unit:N ] .
```

Listing 2: Transformed RDF knowledge graph.

The force values shown (245.2, 189.7, 312.1 N) represent typical operational measurements for aluminum milling operations under normal cutting conditions. The Knowledge Graph Connector transforms this AAS structure into RDF through systematic mapping rules. Listing 2 shows the resulting knowledge graph in Turtle notation, preserving structural information while enriching with explicit semantic relationships including type hierarchies enabling inheritance-based reasoning and physical quantities modeled using QUDT ontology supporting automated unit conversion. The semantic knowledge graph enables sophisticated queries impossible with traditional databases. Listing 3 demonstrates real-time force deviation monitoring identifying equipment operating outside normal parameters by comparing measurements against targets across three axes simultaneously.

```
PREFIX mfg: <http://example.org/ontology/manufacturing/>
PREFIX qudt: <http://qudt.org/schema/qudt/>

SELECT ?system ?axis ?current ?deviation
WHERE {
    ?system rdf:type mfg:MillingSystem ;
            aas:hasSubmodel ?forceSubmodel .
    ?forceSubmodel aas:hasSubmodelElement ?cuttingForces .
    ?cuttingForces mfg:forceX ?currentX .
    ?currentX qudt:numericValue ?current .
    BIND("X" AS ?axis)
    BIND(ABS(?current - 150.0) AS ?deviation)
    FILTER(?deviation > 10.0)
}
```

Listing 3: Force deviation detection.

Listing 4 demonstrates cross-equipment capability discovery based on material requirements and technical specifications, combining multiple semantic dimensions including material compatibility and quantitative constraints.

```
PREFIX mfg: <http://example.org/ontology/manufacturing/>

SELECT ?equipment ?manufacturer ?capability
WHERE {
    ?equipment rdf:type mfg:MillingSystem ;
               mfg:compatibleMaterial mfg:Titanium ;
               mfg:manufacturer ?manufacturer ;
               mfg:processingCapability ?capability ;
               aas:hasSubmodel/mfg:positioningAccuracy ?accuracy .
    FILTER(?accuracy <= 0.010)
}
```

Listing 4: Capability discovery.

4.1 Performance Evaluation

Table 2 presents performance measurements for critical operations in the semantic integration pipeline, averaged over 10 executions to account for JVM warm-up and system load variations.

Table 2: Performance metrics for semantic integration pipeline.

Operation	Time	Execution Context
AAS-to-RDF Transform	118ms	State change trigger, asynchronous
Force Deviation Query	43ms	On-demand SPARQL
Capability Discovery	76ms	On-demand SPARQL
SWRL Inference	227ms	Periodic batch (5-10s), Jena Rules
Write-back to AAS	95ms	Event-driven insights
Graph Storage	2.1MB	10,000 RDF triples (Turtle)
Sensor data sync	8 Hz	Direct AAS (no semantic overhead)

4.2 Real-Time Architecture

The semantic integration employs event-driven architecture optimized for real-time operation. AAS Infrastructure maintains 8 Hz synchronization with physical assets (125ms cycle) using conventional time-series storage. Semantic transformation operates asynchronously: continuous monitoring flows real-time sensor data to AAS at 8 Hz without semantic overhead, while selective transformation (118ms) triggers only on significant state changes rather than every sensor reading. Periodic reasoning (227ms) executes in background threads at 5-10 second intervals, with on-demand queries (43-76ms) executing when intelligence is required. Event-driven synchronization (95ms) occurs only when reasoning generates actionable insights. This architecture ensures the semantic layer enhances rather than impedes real-time control, with high-frequency operational data in time-series storage for immediate access while the knowledge graph provides reasoning for decision support tasks where millisecond response is not critical.

Comparison with traditional databases reveals trade-offs. While simple SELECT queries execute in 5-15ms, they cannot express semantic relationships in Listings 3-4 without complex multi-table JOINs and application logic. SPARQL queries combine material compatibility, equipment capabilities, technical specifications, and process parameters in single declarative statements impossible to formulate efficiently in SQL, justifying additional latency for reasoning-intensive tasks.

4.3 Deployment Experience

The proof-of-concept implementation required approximately 6 person-weeks for initial development, including ontology design (2 weeks with 3 domain expert consultations), transformation pipeline implementation (2 weeks), SWRL rule development (1 week), and integration testing (1 week). Integration with existing PlatinA infrastructure was achieved through standardized REST APIs without modifications to core AAS components, demonstrating the incremental enhancement approach. The containerized architecture enabled seamless deployment alongside existing AAS services with minimal infrastructure changes.

5 DISCUSSION

The semantic enhancement introduces computational overhead (118ms transformation, 227ms reasoning) and implementation complexity (ontology engineering, maintenance) that must be justified by specific requirements. Our analysis suggests knowledge graphs provide maximum value in scenarios characterized by: (1) cross-equipment reasoning where decisions span multiple assets, materials, and processes; (2) dynamic material-process matching where novel combinations arise frequently; (3) implicit relationship inference where capabilities, properties, and requirements must be reasoned over without explicit programming; and (4) knowledge preservation where expert manufacturing knowledge should be captured formally.

Conversely, semantic overhead may not be justified for: (1) simple monitoring where time-series queries suffice; (2) well-defined repetitive processes where rule-based control captures decision logic; (3) single-equipment operations without cross-system dependencies; and (4) environments lacking domain expertise for ontology development. The PlatinA platform demonstrates hybrid deployment where traditional databases handle high-frequency sensor data while the knowledge graph addresses reasoning-intensive tasks. This architectural pattern provides practical balance between performance and intelligence.

The incremental enhancement approach mitigates deployment barriers by maintaining existing AAS infrastructure while introducing semantic capabilities selectively where they provide clear value. Manufacturing facilities can begin with limited integration for specific use cases (equipment selection, maintenance scheduling) and expand coverage as expertise develops, avoiding all-or-nothing adoption challenges hindering semantic technology deployment in conservative industrial environments.
This proof-of-concept demonstrates technical feasibility but has limitations requiring future work.

First, validation with a single milling system limits its generalizability claims across diverse manufacturing equipment types. While PlatinA's AAS infrastructure is designed for 50 concurrent devices and currently integrates 3 systems, semantic integration has only been validated with one proof-of-concept system. Empirical validation across multiple heterogeneous systems under production loads with hundreds of thousands of RDF triples remains necessary to demonstrate scalability from single-system proof-of-concept to infrastructure-wide deployment. Second, ontology engineering and maintenance require specialized expertise in both semantic technologies and manufacturing domain knowledge, potentially limiting adoption in resource-constrained environments. Third, SWRL reasoning performance (227ms per inference cycle) may require optimization strategies such as pre-computation or incremental reasoning for production deployments with complex rule sets exceeding our current 8 rules. Fourth, the proof-of-concept lacks comprehensive evaluation of failure scenarios, error recovery mechanisms, and long-term operational stability in 24/7 manufacturing environments. Finally, while performance measurements demonstrate acceptable latency for decision support tasks, integration with time-critical control loops requiring sub-100ms response may necessitate architectural refinements or hybrid reasoning approaches combining semantic inference with traditional rule engines.

6 CONCLUSIONS

This proof-of-concept validates technical feasibility of semantic AAS integration through hybrid AAS-Apache Jena Fuseki architecture, systematic AAS-to-RDF transformation maintaining IEC 63278 compliance, and SWRL-based automated reasoning for equipment selection, maintenance prediction, and quality assessment.

Practical applications include automated resource allocation through semantic queries over capability ontologies, cross-equipment process optimization identifying compatible tool-material-machine combinations, and predictive maintenance scheduling combining calibration validity, force deviation patterns, and sensor health indicators.

The primary objective of this work is establishing the semantic foundation necessary for cognitive assistance systems supporting manufacturing operators and engineers. This research contributes foundational infrastructure enabling the PlatinA platform to integrate AI-driven capabilities including natural language interfaces for intuitive equipment interaction, intelligent decision support combining machine learning with semantic reasoning, and context-aware assistance adapting to operator expertise levels and current manufacturing scenarios.

The knowledge graph architecture enables AI systems to understand manufacturing relationships, equipment capabilities, and process constraints, facilitating human-AI collaboration where cognitive assistants augment rather than replace human expertise. This work establishes semantic infrastructure enabling the PlatinA platform to integrate AI-driven capabilities including natural language interfaces, intelligent decision support, and context-aware assistance for manufacturing operators through federated knowl-edge sharing across regional networks.

7 FUTURE WORK

Future work will address current limitations through multi-system validation across diverse equipment types to demonstrate generalizability, empirical scalability testing expanding from single-system proof-of-concept to PlatinA's current 3-device deployment and ultimately to the infrastructure's 50-device design capacity, enhanced reasoning capabilities through temporal and probabilistic reasoning, collaborative ontology engineering methodologies, and comprehensive industrial validation assessing long-term stability and ROI.

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An Effective Method of Using Ozone Generator in Viticulture Instead of Pesticides

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Keywords: Photovoltaic, Ozone, Energy Efficient, Cost Efficient. Microelements, Nutritional Value.

Abstract: This study addresses the challenge of developing sustainable and environmentally friendly viticulture practices by proposing an alternative to conventional pesticide use based on ozonated water treatment. The method involves the application of ozone dissolved in water at controlled concentrations, adjusted according to environmental conditions such as rainfall and temperature. Field experiments were conducted over two years in vineyards of the Bolnisi region (Georgia) on different grape varieties, including Saperavi, Chinuri, and Rkatsiteli. The proposed approach demonstrates that ozonated water can effectively replace chemical pesticides while maintaining plant health and reducing environmental impact. Experimental results indicate that the method preserves the chemical composition of grapes, soil, and vine leaves, without increasing heavy metal accumulation. Moreover, an increase of approximately 30% in resveratrol content in vine leaves was observed, while quercetin levels remained stable. The findings confirm that ozone-based treatment represents a cost-effective, energy-efficient, and sustainable solution for viticulture. This approach is particularly suitable for small-scale farmers, as it reduces dependency on agrochemicals and supports the production of safer and nutritionally valuable agricultural products.

1 INTRODUCTION

To achieve global development goals, healthy, sustainable and inclusive food systems are critical, especially in the world's most fragile regions where agriculture and its development are one of the most powerful tools for poverty reduction and are also critical for economic growth.

Three billion kilograms of pesticides are used worldwide every year, while only 1% of total pesticides are effectively used to control insect pests on target plants. The large amounts of remaining pesticides penetrate or reach non-target plants and environmental media. As a consequence, pesticide contamination has polluted the environment and caused negative impacts on human health [1].

The numerous negative health effects that have been associated with chemical pesticides include, among other effects, dermatological, gastrointestinal, neurological, carcinogenic, respiratory, reproductive, and endocrine effects. Furthermore, high occupational, accidental, or intentional exposure to pesticides can result in hospitalization and death [2].

The background paper to The State of Food and Agriculture 2023 examines the annual hidden costs of agrifood systems across 2016-2023 for 154 countries. The expected value of hidden costs is around 13 trillion 2020 purchasing power parity (PPP) dollars [3].

Despite direct annual global pesticide costs, where In 2023, the volume of total pesticides exports (used here as a proxy for trade) decreased by 3 percent compared with 2022 to 6.7 Mt of formulated products, and their value decreased by 12 percent to USD 42.8 billion [4], as well as ongoing and growing "hidden costs", there is still no effective alternative to pesticides that could provide sufficient healthy agricultural products with the less losses for a growing population.

2 MATERIALS AND METHODS

2.1 Ozone Generation Technology

Ozone is approved for use as an alternative disinfectant in the United States and Europe. In the US, the FDA has granted it Generally Recognized as Safe (GRAS) status for use in food and food processing, including as a sanitizer. In Europe, ozone is widely accepted and used in wastewater treatment plants, particularly for disinfection and odor control. Ozone is a strong oxidant and potent disinfecting agent. Even though it is new for the US, it has been utilized in European countries for a long time [5].

The main problems of the mass distribution of ozone technology in the world are the high cost and the high energy consumption of the ozone generators (air; water).

In 2021, in Georgia (GE), was patented (P 2021 7302 B) [6] its own "Ozone Generating System" technology and began to use it in various areas of agriculture. An advantage of the present invention: "Ozone Generation System": can operate reliably for a long time without damaging the electrode due to the current generated during the electric discharge; can operate at a reduced voltage of the power source; can operate efficiently with relatively less energy consumption; ozone generation is carried out by barrier and corona discharge and ultraviolet radiation simultaneously; ozone formation is regulated by air flow and by electric operation mode; the ozone generator operates on oxygen on demand.

2.2 Applications of Ozone Generation Technology for Vineyards

Grapevines are one of the most extensively grown fruit crops in the world and also one of the leaders in pesticide consumption. Worldwide, on average 35 % of all pesticides are used for viticulture [7].

This can be largely explained by the fact that grapevines host the highest number of pathogens of any woody species.

Recent studies have revealed that ozone (O3) in aqueous solution is a promising candidate for limiting grapevine infection by *Phaeoacremonium aleophilum*, a fungus associated with esca. In the last few years, in fact, spraying grapevines with ozonated water for disease control is becoming more frequent among winegrowers. The reason lies mainly in the high oxidizing power of ozone and its spontaneous decomposition to oxygen without forming hazardous residues. The decomposition of aqueous ozone also leads to the production of reactive oxygen species (ROS), which are more reactive but less selective than molecular ozone [8].

Ozonated water is being introduced as an alternative phytosanitary treatment to control grapevine diseases in a context in which the reduction of chemical pesticides has become an urgent necessity [9].

However, it has recently become clear that ozone exposition leads to another important benefit: in living tissues, the induced-oxidative stress triggers the antioxidant response, and, therefore, it enhances the production of antioxidant and stress-related secondary metabolites. As such, ozone can be considered an abiotic elicitor. The goal of the present review was to critically summarize knowledge about the possibility of improving bioactive compounds and, consequently, the health-related properties of grapes and wine, by using ozone [10].

2.3 Scientific Competence and Technical Equipment

Within the framework of the research grant project of the Shota Rustaveli National Science Foundation of Georgia with the support of the Technical University of Georgia, a target group of 11 participants was selected from the vineyards of the Bolnisi District Small Winemakers Association, with whom research was conducted over two years on the use of ozone in the form of an aqueous solution in different concentrations, under different natural conditions, on different grape varieties (*Saperavi, Chinuri, Rqatsiteli*).

Each participant, who provided at least 1 ha of vineyard, was equipped with 585 wat solar panels as a power supply, also by overheating protection systems, AC and DC stability protection, additional charging systems for other electrical appliances, batteries, etc. and 10 gr/h water ozone generators for 15 liters water sprayers, with which water was charged with soluble ozone up to 0.03-0.08 mg/l on demand. Concentration measurements were carried out using a "Hy bono" Dissolved Ozone Tester.

2.4 The Methodology of Application of Ozonized Aqueous Solution in the Vineyard Follows

The application of ozonized aqueous solution in the vineyard was carried out according to a structured treatment protocol developed based on environmental conditions and grapevine phenological stages. The methodology includes the following key steps:

1) Vineyard treatment began in late March - early April and was carried out during 9 phenological phases until the second ten-day period of August with an ozonized aqueous solution at a concentration of 0.03 mg/l. (For prevention of powdery mildew, ash, mites and grape moth (1, 2, 3 generations), scale insects, false scale insects, rot).
2) No treatments were carried out during the flowering period of grapes.
3) During the rainy season at a temperature of 20–29 °C, the vineyard treatment was not carried out, but was resumed out of turn immediately after the rains ended. After a period of 1–4 days of rain, the ozone concentration in the aqueous solution was 0.04–0.06 mg/l. After a period of 6–9 days of rain, the ozone concentration in the aqueous solution was 0.06–0.08 mg/l.
4) After the second ten-day period of August or at a temperature above 30 °C, on healthy and large, then on ripe and, finally, on very ripe large bunches of grapes, the treatment was continued only after rainy days, or for prevention only once, while the ozone concentration in the aqueous solution was 0.04-0,06 mg/l. and 0.03 mg/l. respectively.

During harvesting and visual inspection, the vineyard and berries looked healthy.

3 RESEARCH

The quality of grapes was assessed by the content of some mineral and phenolic components.

Resveratrol scavenges free radicals and enhances the activity of endogenous antioxidant enzymes. This action protects cellular components from damage associated damage and helps reduce oxidative stress, a significant factor in aging and the development of age-related diseases, such as cardiovascular diseases and diabetes [11].

Quercetin manifests antioxidant properties both in vivo and in vitro. Free radical scavenging activity of quercetin protects from various age-associated disorders. A diet rich in quercetin has various health-promoting benefits. It acts as an agent to lower coagulation, hyperglycemia, inflammation, and hypertension. Various clinical studies show that supplementation of quercetin is used to prevent and treat various chronic diseases such as cardiovascular disorders [12].

Since the two main types of antioxidants in grapes - Resveratrol and Quercetin neutralize the effects of free radicals that can cause significant harm to the body, these two main phenolic compounds were analyzed from organic components.

Moreover, it was necessary to determine whether the chemical composition of vine leaves and wine changed as a result of replacing pesticides with ozonized water treatment, therefore, microelements were also determined in vine leaves.

From winemaking companies of the Bolnisi region, wines and grape leaves were used as objects - *Saperavi* and for comparison *Chinuri* and *Rqatsiteli*.

Microelements were determined in wine, soil and grape leaves. Sample preparation and content measurement was carried out in the Atomic Absorption Spectrometry Department of the Academician Nodar Kekelidze Scientific Research Institute of Materials Research of the Faculty of Exact and Natural Sciences of Ivane Javakhishvili Tbilisi State University, on an atomic absorption spectrometer AAnalyst 800 (PerkinElmer Inc.) with software WinLab 32 and in the "Geoanalytic" laboratory of the Alexandre Tvachrelidze Mineral Resources Caucasus Institute. (The results of the analyses are presented below in Tables 1, 2, 3).

Chemical analyses were conducted according to the respective ISO and GOST. In particular, analysis of heavy metals carried out according ISO 8288-1986 standards.

Resveratrol and quercetin assays were performed using the highly efficient liquid chromatography method. We made chromatographic division on Agilent 1200 Technologies chromatograph CI8 HPLC 5mcm chromatographic column. For analysis, 20 ml of the sample was administered with an autosampler, acetonitrile-HPLC, >99.9 % (Sigma-Aldrich), acetic acid, bidistillate were used as eluents. Extraction used 60% ethanol. For chromatographic division, the following conditions were selected: gradient elution with acetic acid, acidified bidistillate, and acetonitrile. Total analysis time 50 minutes.

4 RESULTS AND DISCUSSIONS

As follows from the data in Table 1, the content of heavy metals in Saperavi wines from the ozonized and control plots is almost the same and does not exceed the MAC (except for copper and manganese). When comparing the amount of heavy metals in wine and soils of the studied plots (Tables 1 and 2), it was found that almost a thousandth part of each heavy metal contained in the soil passes into the wine.

Table 1: Heavy metal content in bottled wine, mg/l.

N	Element	Cu	Zn	Pb	Cd	Co	Ni	Mn
1	Saperavi from non-ozonized site	1.114	0.912	0.120	0.00	0.022	0.072	0.836
2	Saperavi from ozonized site	0.136	1.200	0.113	0.00	0.017	0.107	0.152
3	MPC (maximum permissible concentration)	1.0	5.0	0.3	0.001	0.2	0.5	50.0

Table 2: Content of mineral microcomponents in soil, mg/kg.

N	Element	Cu	Zn	Pb	Cd	Co	Ni	Mn
1	Non-ozonized site	297.2	820.8	55.3	2.3	9.4	32.6	895.4
2	Ozonized site	312.7	80.3	46.9	1.3	6.1	32.9	820.8
3	MPC (maximum permissible concentration)	3.0	23.0	6.0	0.5	5.0	4.0	60-700

Table 3: The content of some mineral micro components in the vine leaves, mg / kg.

N	Grape	Ni	Cd	Cu	Pb	Mn	Co	Zn	Cr	Fe total
1	Saperavi	27.32	0.56	9.32	1.38	564.5	2.64	7.77	1.75	352,8
2	Chinuri	25.46	0.52	9.41	4.82	120.75	2.44	4.95	2.34	560.0
3	Rqatsiteli	26.98	0.55	9.65	4.84	61.0	2.35	5.75	1.95	266.0

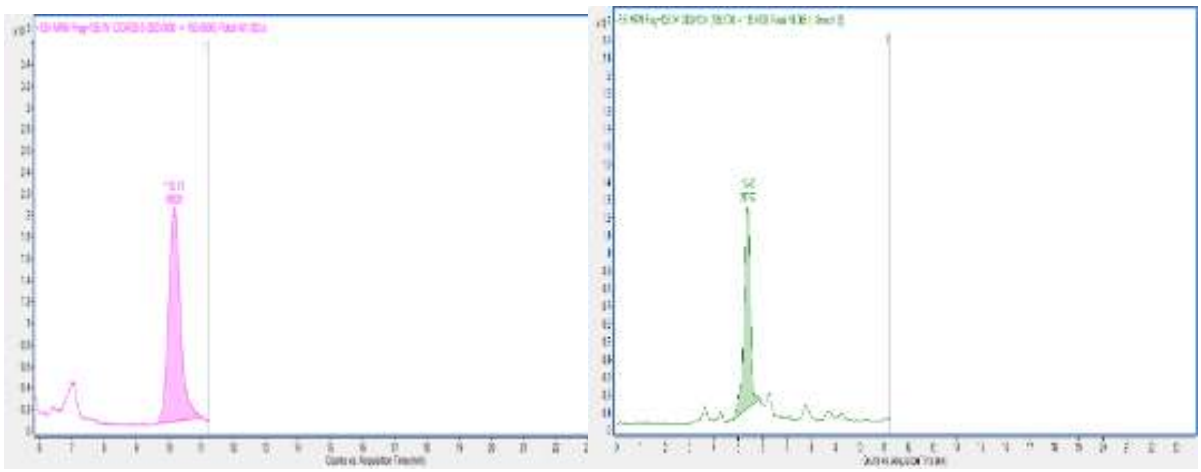


Figure 1: Chromatograms of resveratrol (at the left) and quercetin in leaves from non-ozonated site.

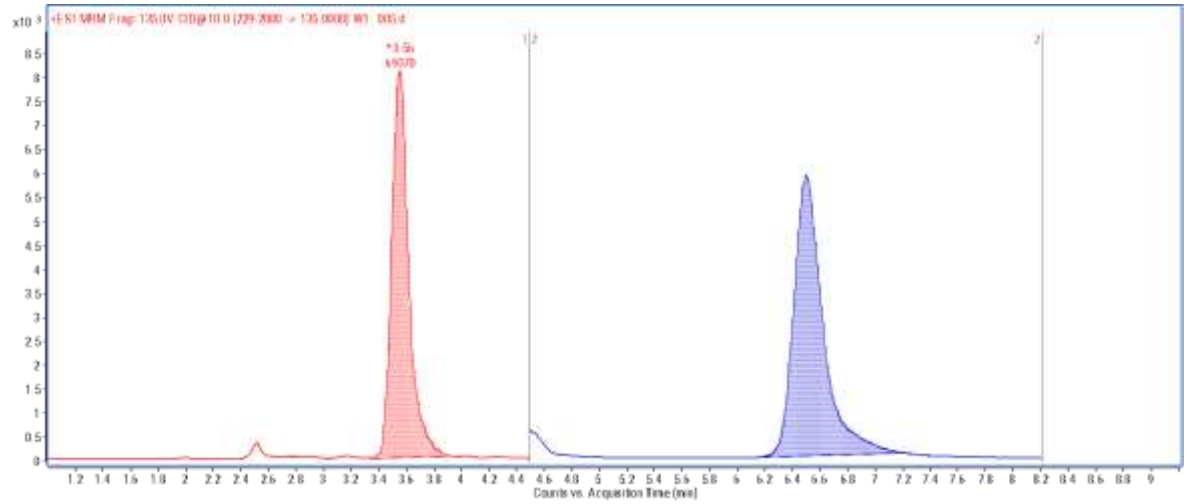


Figure 2: Chromatograms of resveratrol (at the left) and quercetin in leaves from ozonized site.

The content of heavy metals in the vine leaves of three wine varieties is almost the same order of magnitude (except for iron and manganese) and indicates their partial migration from the soil to the vine leaves Tables 2 and 3.

About 3% of copper and lead, 9.7% of zinc, 24% of cadmium, 28% of cobalt and about 80% of nickel passed from the soil to the leaves. According to the data, a study in field vegetation chambers to determine the effect of ozone and simulated acid rain (SAR) on the content of heavy metals in the soil [13].

This indicates high mobility of mobile forms of nickel and cobalt, and such a spread is apparently due to the presence of a large number of mobile forms of some elements and a smaller number of others in the vineyard soil. This was observed both for the ozonized plot and for the control one.

According to the obtained chromatograph mass spectrometric data (Fig. 1), the amount of resveratrol in the leaves of the *Saperavi* variety from the non-ozonized area is 3.4 mg/kg, and quercetin is 13.5 mg/kg (Fig. 1); in the leaves of *Saperavi* from the ozonized vineyard, the content of resveratrol reaches 5.3 mg/kg, and quercetin is 14 mg/kg (Fig. 2).

That is, the amount of resveratrol increased by 30% compared to the vine leaves from the non-ozonized area. In the wine, an inverse relationship with the treatment with ozonized water was observed: 1.64 mg/kg of resveratrol in the ozonized sample and 2.5 mg/kg in the control. The content of resveratrol in this case decreased by 30%.

5 CONCLUSIONS

The results of this study demonstrate the effectiveness of using ozonized aqueous solutions as an alternative to conventional pesticide treatments in viticulture. Based on the conducted experiments and analysis, the following conclusions can be drawn:

1) The use of ozone generators, available to smallholders, through above mentioned method of cultivation, reduces their annual costs for pesticides and toxic chemicals. Reduces the pressure on the environment;
2) Energy-efficient technologies are more flexible in switching to solar energy, especially for smallholders;
3) The use of an aqueous ozone solution for treating vineyards instead of chemicals and pesticides does not cause any negative impact on the chemical composition of the leaves and the resulting wines from the *Saperavi* variety;
4) The content of heavy metals in the vine leaves indicates their partial migration from the soil through the root system and trunk into the vine leaves and in wine for both grapes, from the ozonized area and those obtained from the area treated with pesticides;
5) As a result of ozonation, an increase in the amount of resveratrol was observed in vine leaves from the ozonized area and a decrease in the amount of resveratrol in wine from the ozonized area;
6) As a result, replacing traditional pesticide treatment with ozonation and this method, reduces the overall content of toxic substances in the resulting wines, which is the positive effect of using an aqueous ozone solutionthrough this method for spraying the vineyards.

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Development of a Wearable Exoskeleton for Active-Assist Knee Flexion-Extension

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Keywords: Lower-Limb Rehabilitation, Wearable Exoskeleton, Active-Assist Device, Rehabilitation Robotics.

Abstract: Lower-limb rehabilitation exoskeletons have arisen as effective instruments for aiding patients with mobility issues in their recovery process and addressing the difficulties encountered by physical therapists, such as staff shortages and the physically demanding nature of repetitive sessions. Nonetheless, research has also shown that patients frequently develop a reliance on the passive assistance provided by such devices, which may result in a decline in the yield that can be acquired from rehabilitation training sessions. With this, the study highlights the development of a wearable exoskeleton for active-assist knee flexion-extension that can be adaptable and work in conjunction with other existing rehabilitation devices for knee movement. This system provides emphasis on the principle of effort, which in return results in the objective of the study in detecting motion intention and angle change for a period of every 100 milliseconds. Based on the obtained values, a control signal with knee flexion or knee extension as output would be provided if and only if the developed exoskeleton detects motion intention from the user but no change in angle was produced – denoting that the user's strength may not be enough to perform the intended action. This ensures the active participation of patients in their physical therapy sessions. Allowing for a mechanical input rather than utilizing physiological signals revealed great potential in reducing the risk of acquiring noisy data. Experimental results show that the developed exoskeleton has achieved a classification accuracy of at least 90% for detecting changes in angle and motion intention.

1 INTRODUCTION

According to the Global Stroke Fact Sheet 2022 of the World Stroke Organization [1], stroke remains to be the leading cause of long-term disability worldwide and the second leading cause of death with a global incidence of more than 12.2 million annually while the overall prevalence of stroke was found to be over 101 million individuals. This led to an estimated loss of 0.66% of the global gross domestic product [2]. In addition, with the increase in the average life expectancy of humans, the elderly population is rapidly increasing, and this is known to be closely interrelated with the increasing incidence of long-term ailments and disabilities wherein according to the United Nations [3], over 46% of older people globally, those aged 60 years and over, are considered as persons with disabilities (PWDs).

To address physical and mobility impairments, physical rehabilitation and are recommended to patients to recover their balance and mobility, in combination with other treatments to trigger neuroplasticity [4]. An effective rehabilitation is a customized process that is tailored to the individual needs of a patient. Designing rehabilitation programs for learning or relearning a motor skill includes the following principles: 1) practice, 2) skill specificity, 3) feedback, 4) attention, and 5) interest. As such, existing methods of physical therapy, specifically traditional rehabilitation and robotic rehabilitation processes, are performed on patients to address and cover the principles for motor learning. Conventional physical therapy heavily involves intensive labor provided by physical therapists (PT) and physicians, which is expensive and inefficient [5], [6]. With robotic rehabilitation, a physical therapist can attend

to more patients at a time, which maximizes the PT's efficiency and potentially lowers the rehabilitation costs per patient as robotic assistive devices aid in eliminating manual assistance provided by the PT while performing with better motion accuracy, allowing the PT to focus more on performance evaluation and analysis of the patient [5], [7].

According to the study of Taravati et al. [8], patients have the tendency to develop a dependency on passive movements, which can lead to a decrease in active, voluntary movements. Rehabilitation devices that assist patients in performing passive-assisted ROM exercises are found to be less effective than active exercises [9]. Nonetheless, they are both similarly efficacious in improving individuals' functional fitness [10].

The performance of prosthetics and orthotics devices highly relies on their control algorithms as they specify how the robot or device would carry out its tasks and how it would react to external factors that may be brought on by the environment or the subject. With this, the assistive control strategies developed to aid subjects with insufficient muscle contraction to produce the desired movement and help them trigger neuroplasticity, the ability of the brain to rewire itself and bring back the sensory and motor functions of patients [11].

Powered orthoses for rehabilitation are continuously being studied and researched as robotic rehabilitation is still considered to be an emerging technology in today's Industry 4.0. These devices generally aim to aid PTs as well as patients in maximizing their therapy sessions to achieve a maximized gain; furthermore, these often employ sensors to obtain data that would be utilized for feedback to the PT, ensuring that the PT has quantifiable data about the patient's performance.

Based on the different literature discussed above, there is extensive research on the application of force sensors, inertial sensors, and EMG sensors. Most studies show that effort plays an important role in physical rehabilitation, often applying force sensors, inertial sensors, and/or EMG sensors to the device to obtain this information. In addition to that, there are also few to no studies on the development of an exoskeleton that is capable of being integrated with another existing rehabilitation device; thus, this paper aims to contribute to the existing literature by incorporating mechanical sensors to detect physical movement and effort of the subject to minimize error and data noise while being able to provide a control signal to the rehabilitation device that is connected with the system and assist the subject once needed.

1.2 Limitations of Current Control Strategies for Robotic Rehabilitation Technologies

Several limitations and challenges associated with existing rehabilitation assistance approaches can be identified:

1) Counterbalancing assistance is highly beneficial in performing activities that require a greater level of ROM; nevertheless, having a mechanical counterpart is as important to ensure the safety of the patient.
2) Impedance-based assistance may lead to the patient's passiveness over the training session, just after the patient produces enough effort to trigger the robot's assistance.
3) Lastly, EMG is helpful in monitoring muscle activation, but it is highly sensitive to several external factors – leading to the need to calibrate for every patient and every training session.

While these control strategies display promising results in assisting physical therapists and patients in performing rehabilitation exercises, one of the important points to consider is the accuracy of movement pattern assessment of the patient and the engagement of patients in various activities beyond structured therapy sessions.

Paper Contribution. The study specifically intends to determine and accomplish the following: (1) to develop of a 1-DOF wearable exoskeleton for active-assist knee flexion-extension; (2) to be able to measure and motion intention and change in angle produced by the human subject with a classification accuracy of at least 90%; and (3) to provide control signal based on the parameters obtained from the subject.

2 MATERIALS AND METHODOLOGY

Devices targeting physical rehabilitation are generally based on traditional rehabilitation practices in which a PT must manually assist the patient in performing therapy exercises, depending on the type and level of assistance needed by the patient. Concurrently, the PT senses and is aware of the patient's response to the assistance provided. Applying this concept, as illustrated in Figure 1, peripherals allowing for input are attached to the user

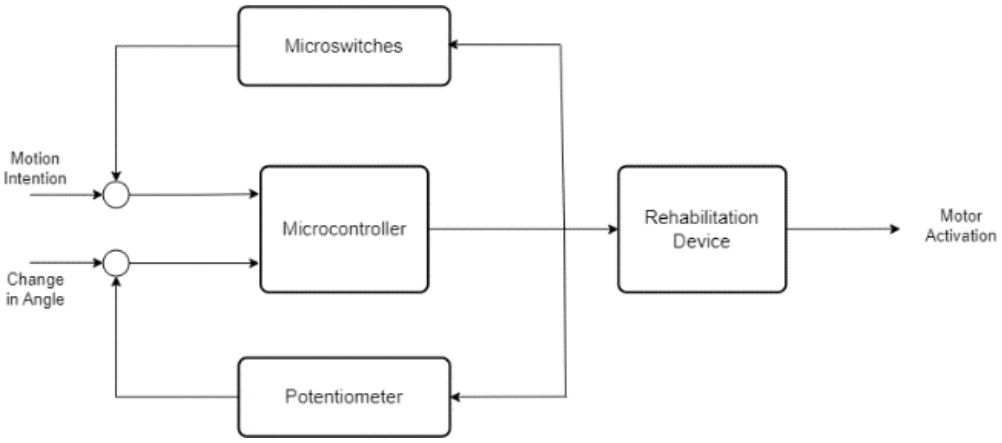


Figure 1: Control system for signal acquisition.

to determine his/her intention for movement and provide these feedback parameters to the microcontroller that is programmed with a control algorithm that would decide upon the response of the overall system – ensuring the patient's active participation throughout the therapy session.

Literally meaning the "outside skeleton", an exoskeleton is an external frame that can be worn to support an animal's body shape and works in conjunction with its user. This is typically made from rigid materials such as carbon fiber or fiberglass, but it can also be fabricated using soft and elastic materials such as wearable straps. For potentiometer placement, a simple linkage employing a revolute joint was applied. On the other hand, the device setup was simulated to be fabricated in actual using aluminium alloy 5083, as presented in Figure 2.



Figure 2: Developed exoskeleton with a human dummy.

2.1 Control Algorithm

In this study, a control signal would only be provided to the rehabilitation device to provide assistance if and only if the system has observed that the subject intends to move but has not produced an angle difference for a period of 100 milliseconds (ms). Shown in Table 1 is the truth table for the developed system.

Table 1: Truth table for the developed Wearable Exoskeleton.

Motion Intention	Angle Change	Control Signal for Motor Actuation
0	0	0
0	1	0
1	0	1
1	1	0

2.1.1 Arduino UNO

This microcontroller is used to monitor if the subject exerts physical effort and assist when the need arises to foster motor recovery. A control signal would only be provided to the rehabilitation device to provide assistance if and only if the system has observed that the subject intends to move but has not produced an angle difference for a period of 100 milliseconds (ms).

2.1.2 Normally-Open Micro Limit Switches SS-01GLP SPDT

Two microswitches are utilized to ensure that effort is given to perform the intended action – serving as the effort monitoring system of the study that aims to detect motion intention that could not be recorded by the change in angle (potentiometer). One microswitch is positioned at the anterior shank to measure the effort exerted by the subject during knee extension. In contrast, another microswitch is placed at the posterior compartment of the leg, also referred to as the calf, to detect efforts or motion intention in performing the knee flexion.

2.1.3 B10K Rotary Potentiometer

To ensure that the intended motion exerted by the subject is sufficient to be translated into movement, a B10K rotary potentiometer that has a resistance of 10K ohms, also known as the rotary angle sensor, is implemented as redundancy to increase the reliability of the system, which acts as the verification step of the process, before physical assistance is generated by the rehabilitation device connected to the system that would assist the subject in performing the action. In conventional PT practice or any physical activity, human movement is analysed based on visual observation [12].

2.2 Signal Acquisition

Both the motion intention and the angle difference are measured at a regular time interval. To determine the threshold value and the potentiometer's sensitivity, initial testing of the developed system was performed wherein the subject was at rest with the subject's leg at a 90-degree angle (with foot flat on the ground). Sampled at 100ms intervals, an experiment that lasted for 10 seconds long was conducted, resulting in a total of 100 samples. The absolute values of the recorded data were obtained for this experiment, as shown in Figure 3.

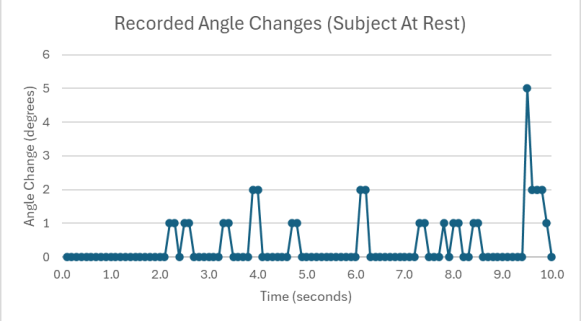


Figure 3: Recorded angle changes for potentiometer threshold (Subject at Rest).

It can be observed from the figure above that the potentiometer often plays its angular reading from 0 to 2 degrees (with an outlier of 5 degrees), even without the human subject producing any movement. As such, the threshold value for the variable resistor was set to +/- 2 degrees. At the same time, two normally-open micro limit switches SS-01GLP SPDT (single-pole-double-throw relay) are utilized to ensure that effort is given to perform the intended action – serving as the effort monitoring system of the study that aims to detect motion intention that could not be recorded by the change in angle (potentiometer).

2.3 Target Exercises

The subject was guided to perform the assigned exercise. In this study, knee flexion and extension were the specific tasks to test the developed exoskeleton. For knee extension, the subject was asked to sit upright with their thigh supported in a chair and with the left knee starting from a 90-degree angle and then stretch the leg out as far as possible, having about an angle of 180 degrees from a human's thigh and calf or is parallel to the ground. On the other hand, especially for powered and stationary rehabilitation exoskeletons that consist of actuators, similar to the TAYÔ prototype of the Institute of Biomedical Engineering and Health Technologies (IBEHT), the knee flexion refers to the movement of bringing the calf back down to the ground, having about an angle of 90 degrees, also measuring between the thigh and calf. These exercises aim to help strengthen the thigh muscles and regain the knee's range of motion. Figure 4 represents the knee flexion-extension exercise.



Figure 4: Knee flexion-extension [13].

3 RESULTS AND DISCUSSION

This chapter presents relevant data and results gathered from this study. A total of 30 trials were performed to determine the classification accuracy of the developed system, in which its data were recorded at a sampling rate of 100 milliseconds. Material Comparison.

3.1 Developed Exoskeleton

Wearable straps and simple linkages were to be implemented in an attempt to make the wearable exoskeleton more appropriate for human interaction. The mechanical aspect of the study is a 1-DOF wearable exoskeleton that was designed using aluminum alloy 5083 to monitor the knee flexion-extension movement of the left leg and send control signals to assist the subject. This was tied to the supposed existing rehabilitation device wherein microswitches were used to detect motion intention. A clearance was found in which the microswitch lever is touching the subject's skin surface, without pressing the switch button, for knee extension. Foams were also incorporated to carry the subject's partial leg weight and not immediately press the limit switch positioned at the subject's calf, specifically during the knee flexion exercise – to ensure that the force downward is generated by the subject and not gravity. Figure 5 displays the materials used for the microswitch mechanism.

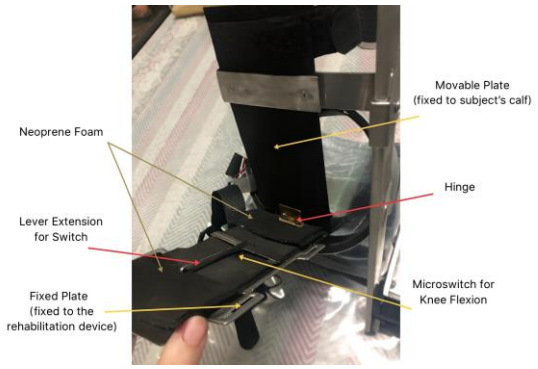


Figure 5: Materials for the microswitch mechanism for knee flexion.

3.2 Motion Intention

Figure 6 describes the classification accuracy for motion intention based on the experiments elaborated above. Results show that the developed exoskeleton is able to detect the motion intention of the subject at 98.73% classification accuracy, which satisfies the objective specified in Chapter I. Due to the peripherals that were used to detect motion intention, it was found that data for motion intention produced little to no noise as compared to using EMG sensors or accelerometers; however, they are highly reliant on the hardware design of the exoskeleton, specifically the placements of the microswitches and the clearance that was manually set for knee extension.

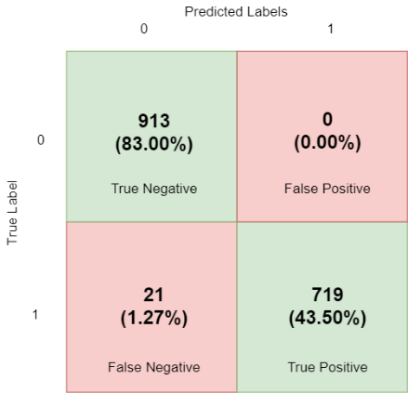


Figure 6: Confusion matrix for motion intention (overall).

3.2.1 For Knee Extension

This subsection aims to evaluate the performance of the exoskeleton when executing the knee extension exercise, starting from the 90-degree angle.



Figure 7: Experimental setup: motion intention for knee extension.

With this, the exoskeleton was only activated by the microswitch positioned in the anterior part of the shin, and any input from the microswitch that was intended for knee flexion was neglected. A fixed wooden rig was used to act as the rehabilitation device for the developed exoskeleton, wherein the lower plate of the exoskeleton was tied to this fixed rig (Fig. 7). For every trial for the knee extension movement, 5 to 6 movements were performed, and a total of 4 trials were performed. As can be observed, control signals provided by the exoskeleton for motor activation primarily generated a zero output, as it could be assumed that the subject is capable of performing the exercise without any external assistance. A classification accuracy of 97.89% was achieved. A higher false value can be observed from the experiments focusing on knee extension, which can be caused by the manual measurement of clearance between the skin surface of the subject and the microswitch as shown in Figure 8.

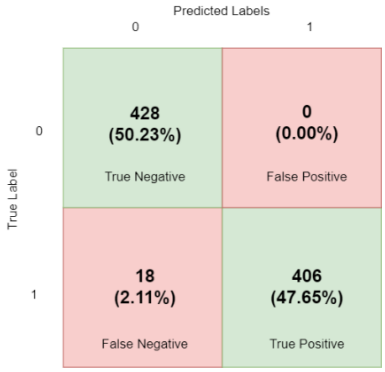


Figure 8: Confusion matrix for motion intention (extension).

3.2.2 For Knee Flexion

For knee flexion, only the microswitch located at the calf is activated for motion intention detection. Due to the design of the exoskeleton wherein a movable plate is hinged to the fixed portion of the exoskeleton calf, the weight of the leg is countered with foam placed in between the fixed and movable plates; furthermore, the microswitch would only be actuated once the user produces force downward, indicating motion intention rather than just gravity performing its duty. To test the effectiveness of the prototype, a chair was utilized to serve as the fixed portion of the existing rehabilitation device. It is vital to note that when the leg is at rest, motion intention shall not be recorded unless a force downward is produced. Figure 9 illustrates how the experimental setup was done.



Figure 9: Experimental setup: motion intention for knee flexion (180°).

A total of 4 trials were also performed by the human subject with five (5) movements per trial. This also proved that the offset of 1 to 2 degrees was achieved for the subject to activate the microswitch. Similar to the results of the previous subsection, control signals produced by the exoskeleton system are mostly zero or off. Displayed in Figure 10 is the confusion matrix for the motion intention of the subject when performing the knee flexion exercise.

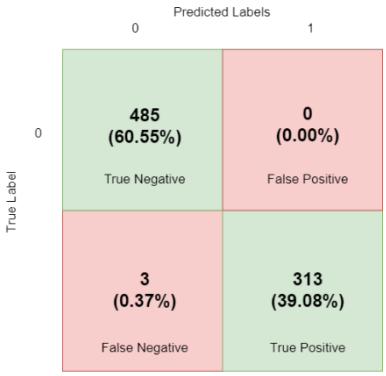


Figure 10: Confusion matrix for motion intention (flexion).

The accuracy of angle change detection was measured by performing the knee flexion-extension freely and completely, starting from the 90-degree angle to the 180-degree angle. A negative angle change denotes a knee extension movement, while a positive change indicates a knee flexion movement. A total of 4 trials (with 5 movements per trial) were performed for this subsection of the experiment. The system would only consider the angle change as a movement if it detected an angle change of at least 3 degrees, whether positive or negative.

By ensuring that the thigh portion of the exoskeleton is fixed when performing change in angle readings, the overall classification accuracy of the developed exoskeleton in detecting change in angle is at 97.55%, as shown in Figure 11. It can be observed that during the course of movement of the healthy subject's leg, there were instances that change in angle was not detected (false negative); this may be attributed or dependent to the speed of the subject's leg or leg fatigue in performing the experiment for that specific period.

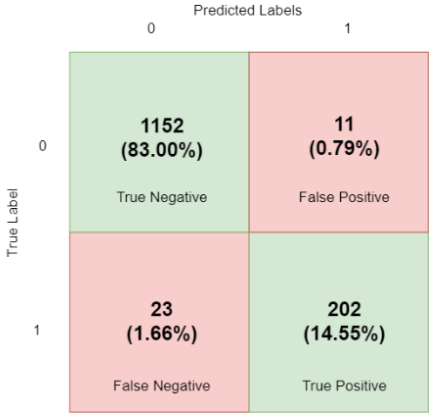


Figure 11: Confusion matrix for change in angle (overall).

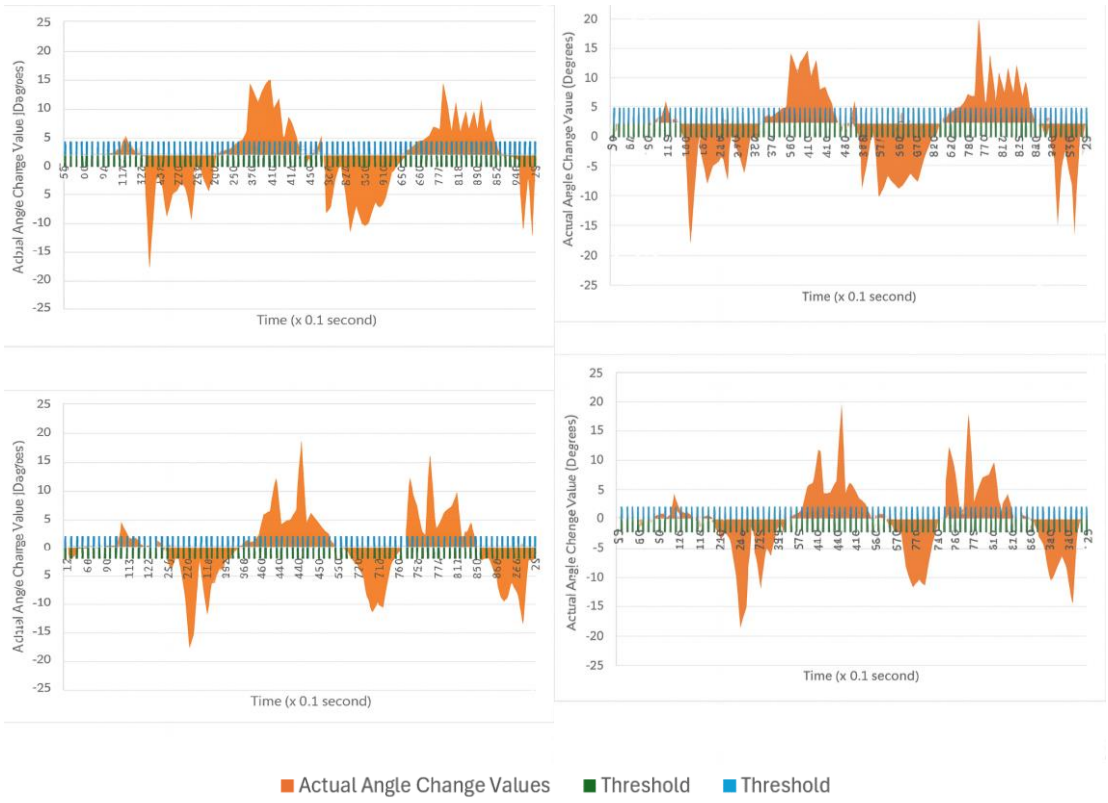


Figure 12: Change in angle vs set angle threshold.

Figure 12 illustrates the pattern of movement of the subject for all 4 trials where the obtained values for angle change were plotted along with the corresponding threshold values of +/- 2 degrees. It can be observed that for all trials in this experiment, the system only considers it as a "change in angle" if and only if the obtained value exceeded the angle threshold that was set.

4 CONCLUSIONS

Allowing for mechanical input into the exoskeleton provides a solution to noisy data often generated by sensors that do not require a mechanical operation, eliminating the risk of being affected by external factors. The obtained information for the required parameters proved that the developed system achieved a classification accuracy of at least 90%. The control signal, whose primary purpose is to instruct the connected rehabilitation device to provide assistance to the user, is dependent on the obtained values for motion intention and the reading for the angle difference. As future directives to develop further and confirm this research's initial findings, it is recommended to perform the following:

1) To implement an exoskeleton with additional degrees of freedom to imitate the actual behaviour of the knee.
2) To explore the applicability of the concept to different 1-DOF target exercises such as but not limited to bicep curls, lateral raises, etc.
3) To create a study or experiment to determine the least amount of force needed to actuate the microswitches.
4) To test the prototype with an actual existing rehabilitation device in order to provide more valuable information that would aid to the improvement of the exoskeleton.

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Development of a Low-Cost Device to Monitor and Alert Prolonged Sitting Posture

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Keywords: Prolonged Sitting, Sedentary Lifestyle, Ergonomics, Posture Monitoring, Arduino-based Device, Wearable Health, Health Technology.

Abstract: Prolonged sitting is a significant public health problem, associated with musculoskeletal pain, hypertension, fatigue, and decreased productivity. Existing solutions such as wearable IMUs, computer-vision systems, and mobile apps are often costly, intrusive, or dependent on sustained user engagement, limiting their practical adoption. This study presents a low-cost, non-intrusive device designed to monitor prolonged sitting and provide real-time auditory alerts to encourage movement breaks. The system integrates an ultrasonic sensor with an Arduino microcontroller programmed with a 60-minute countdown timer; the alarm is triggered if the user remains seated beyond this period. The device was tested with 90 participants (50 students, 20 office workers, 20 faculty), achieving a detection accuracy of 93.4%, with a false positive rate of 4.2% and false negative rate of 2.4%. User evaluation showed high acceptance, with financial feasibility rated 4.13/5, hardware accessibility 4.21/5, and perceived health benefits 4.55/5. Limitations include lack of posture-specific monitoring, basic alert modes, and limited portability. Future improvements will focus on AI-based posture recognition, enhanced sensor calibration, mobile app integration, and wireless operation for broader usability and ergonomic monitoring.

1 INTRODUCTION

Sitting refers to a sustained posture of being seated, typically while engaged in tasks such as reading, writing, or computer use [1], [2]. It has become the most prevalent working habit in modern society, but its prolonged practice often leads to musculoskeletal problems, including poor neck posture, reduced cervicothoracic muscle activity, and fatigue – particularly among students and office workers [3]. In addition to occupational tasks, activities such as television viewing and commuting further increase sedentary exposure, with adults spending nearly 70% of their waking hours, or about 7.7 hours daily, in a seated position [4]. Evidence indicates that relatively short uninterrupted sitting bouts (≈20–40 min) can have adverse cardiometabolic effects and are best interrupted regularly with short movement breaks [5] - [7].

Extended sedentary periods have been linked to hypertension, muscular fatigue, reduced job performance, and physical discomfort in the shoulders, back, thighs, and knees [8]. Breaking these periods with light to moderate activity – such as standing or simple exercises – has been shown to yield both physical and cognitive benefits [9], [10]. In the Philippines, the Occupational Safety and Health Standards (OSHS) highlight the importance of workplace interventions to mitigate such risks [11].

To address this issue, researchers have explored various approaches, including mobile apps, self-monitoring devices, simulation-based interventions, and sensor-based systems for posture or sedentary time detection [12], [13]. Wearable technologies employing inertial measurement units (IMUs) and microelectromechanical systems (MEMS) have also gained traction, enabling machine-learning classification of different postures [14]. More recent innovations integrate AI-driven monitoring, IoT-enabled ergonomics, and mobile health (mHealth) solutions, providing real-time feedback to users [15] - [17].

Despite these advancements, challenges remain. Wearable devices can be intrusive and require continuous compliance. Computer-vision

approaches offer high accuracy but raise privacy concerns and demand costly equipment and controlled environments. Mobile apps, meanwhile, depend on user engagement, which limits their long-term adoption. These gaps underscore the need for a low-cost, unobtrusive, and user-friendly solution that prioritizes sitting duration monitoring rather than complex posture recognition.

This study addresses that gap by designing and developing a device capable of automatically detecting prolonged sitting without requiring user input. Unlike existing methods, the proposed device emphasizes simplicity and accessibility. It operates independently of body weight, age, or posture details, focusing instead on sitting duration as the primary variable. Developmental research methodology guided the process, ensuring both practical functionality and design principles for future ergonomic monitoring tools [18].

Contributions. This study makes three key contributions:

1) It introduces a cost-effective, non-intrusive device for prolonged sitting detection that avoids the limitations of wearables and camera-based systems.
2) It compares current solutions – including IMUs, Kinect, mobile apps, and computer vision – highlighting the trade-offs relative to the proposed approach.
3) It situates the device within recent trends in wearable sensors, AI-driven recognition, and IoT ergonomics, offering practical insights for educational and workplace applications.

2 METHODOLOGY

2.1 System Design and Operation

The device was built around an Arduino Uno microcontroller, which processed input from an ultrasonic sensor mounted at chair level to detect the presence of a seated user. Once detection occurred, the microcontroller initiated a 60-minute countdown timer. If the timer reached zero while the user remained seated, an active buzzer alarm was triggered. The device reset automatically once the user stood up. A 16×2 LCD module provided real-time status updates such as “Active,” “Countdown,” or “Alarm.”

The hardware design integrated the ultrasonic sensor, Arduino controller, LCD, and buzzer, powered by a regulated 5V supply. For software implementation, the Arduino IDE was used to program detection, timer, alarm, and reset functions. Serial monitoring assisted debugging and validation.

Data collection involved logging detection events, timer performance, and alarm activations. Researchers cross-checked device outputs with direct observations to ensure alignment between sensor readings and actual sitting or standing behavior.

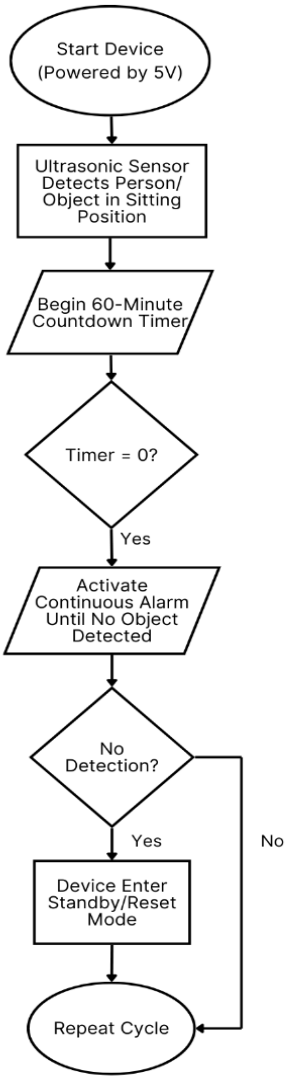


Figure 1: Flowchart of device functionality.

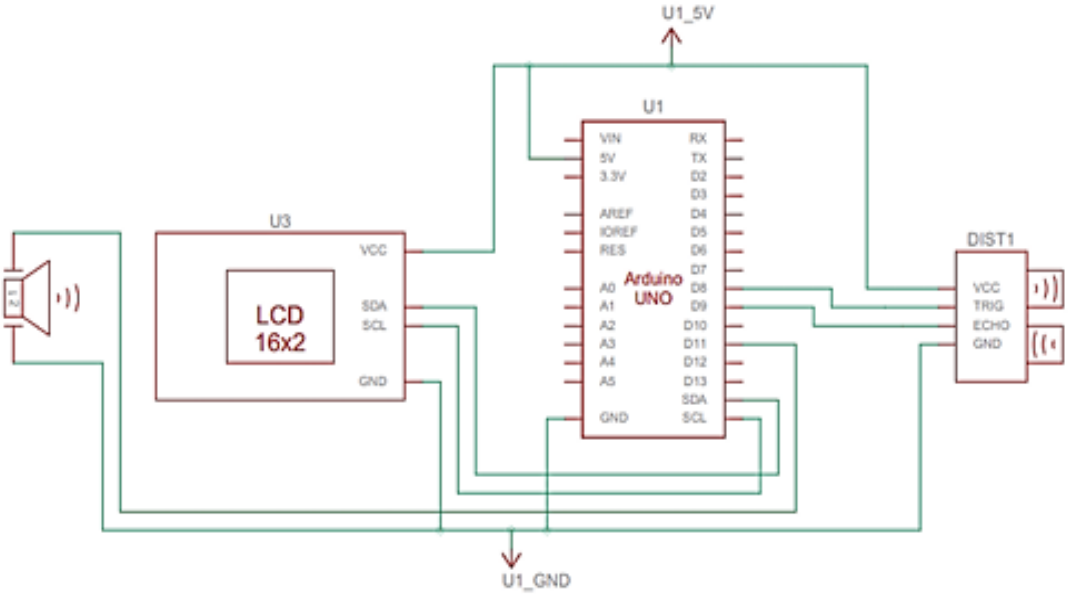
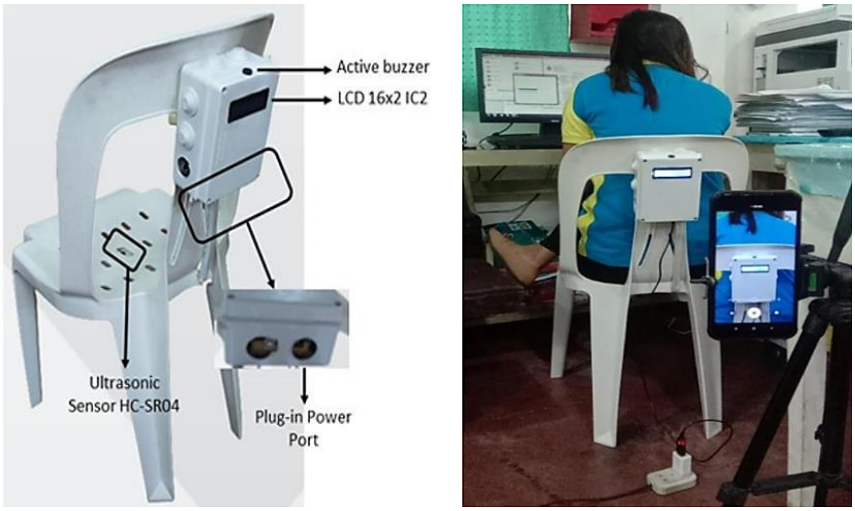


Figure 2: Device schematic diagram.



(a) (b)

Figure 3: Design and implementation of the developed low-cost device for monitoring and alerting prolonged sitting posture: a) device design and hardware components; b) implemented prototype and system setup.

2.1.1 Algorithm Workflow

The device followed a structured operational cycle:

1) Initialization – Power on (5V regulated supply).
2) Occupancy Detection – Ultrasonic sensor checks for user presence.
3) Signal Processing – Detected signals transmitted to Arduino.
4) Countdown Timer – 60-minute timer begins when sitting is detected.
5) Alarm Activation – Continuous alarm triggered when timer reaches zero.
6) Reset Mode – Alarm stops once user stands up and detection ceases.
7) Cycle Repetition – System resets to standby for continuous monitoring.

Figures 1 and 2 illustrate the functional flowchart and hardware schematic, respectively. Figure 3 shows the physical design integrated into a standard chair, with real-time LCD feedback and buzzer alerts validated in both office and classroom settings.

2.1.2 System Performance Evaluation Sensor Calibration

To ensure reliable operation, the ultrasonic sensor was calibrated within a 30–80 cm detection range, corresponding to the average torso-to-sensor distance in typical seating setups. Twenty repeated measurements per increment were taken to refine the threshold. The final range minimized false positives (detecting non-users) and false negatives (failing to detect seated users). Tests were performed in a controlled environment to reduce interference.

2.1.3 Error Rate Assessment

Two error types were logged across 50 trials: (1) false detection (triggering without a seated user) and (2) missed detection (failure to recognize a seated user). Results showed an average false detection rate of 4.2% and a missed detection rate of 2.4%, comparable to error rates reported in other low-cost sedentary behavior monitoring systems [19] - [21].

2.1.4 Validation Protocols

Validation involved 10 participants performing 60-minute seated trials, each repeated three times (30 sessions total). Researchers monitored the countdown timer, alarm activation, and reset function, comparing device outputs with direct observation. The device consistently activated alarms at the 60-minute mark and reset promptly when participants stood up, confirming reliable performance under realistic conditions.

3 RESULTS AND DISCUSSION

3.1 Functional Performance

Initial trials confirmed that the prototype operated as designed. The sensor accurately detected occupancy, the LCD displayed appropriate system states, and the buzzer provided clear auditory alerts. Further testing determined that chair-seat placement yielded superior performance compared to backrest placement, achieving reliable detection within 2–30 cm.

The device achieved 93.4% detection accuracy across 30 trials, with a false positive rate of 4.2% and a false negative rate of 2.4%. A one-sample t-test ($p < 0.05$) confirmed accuracy significantly above 90%. ANOVA results ($F = 5.62$, $p = 0.021$) indicated significant differences by sensor placement, supporting seat-mounted configuration as optimal.

3.2 Respondent Evaluation

3.2.1 Financial Feasibility

Respondents rated the device as financially viable (mean = 4.13), with Arduino hardware particularly affordable (mean = 4.21) [22], [23].

3.2.2 Resource Availability

Accessibility was rated moderately attainable overall (mean = 3.94), with Arduino software highly accessible (mean = 4.28). Sensors and shields were rated slightly lower (means = 3.70–3.92).

3.2.3 Market Feasibility

Respondents perceived high potential market acceptance (mean = 4.32). Health benefits (mean = 4.55) and institutional interest (mean = 4.40–4.48) scored particularly well, while local market demand scored moderately (means = 4.05–4.10), indicating room for awareness efforts.

3.2.4 Comparative Insights

Compared to commercial trackers [19] - [21], the prototype achieved similar accuracy but at a fraction of the cost. Unlike wearable IMUs [14] or vision-based systems [16], it required no intrusive equipment or controlled settings. Its balance of affordability and reliability makes it suitable for schools and workplaces with limited resources.

3.2.5 Strengths and Limitations

Strengths:

- High accuracy (>90%) despite low cost.
- Non-intrusive (no wearables required).
- Simple, accessible Arduino-based design.

Limitations:

- Sensitivity to posture changes (leaning forward/sideways).
- Limited portability (chair-integrated sensor).

- Basic alert modes (buzzer/LCD only, no app/cloud integration).

These findings highlight the potential of low-cost alternatives to address sedentary risks while acknowledging areas for future enhancement.

4 CONCLUSIONS

This study developed and validated a low-cost device for detecting and alerting prolonged sitting using an ultrasonic sensor, LCD, and buzzer. Results demonstrated reliable detection and consistent alarm activation, confirming its suitability for office, classroom, and home environments. The device offers a practical, accessible alternative to wearable or camera-based systems, supporting musculoskeletal health and reducing risks of sedentary behavior.

Improvements should focus on integrating mobile applications for real-time feedback, AI-based posture recognition for slouch detection, and enhanced calibration for diverse users and seating contexts. Wireless operation, rechargeable batteries, and long-term user trials would further improve usability and adoption. With these refinements, the device could evolve into a comprehensive posture-monitoring solution for educational, occupational, and domestic environments.

ACKNOWLEDGEMENT

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Edge-Based Control Framework with Semantic Command Interpretation for Residential Automation

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Keywords: Smart Home Automation, Natural Language Processing, Edge Computing, Ukrainian Language Model, MQTT Protocol, Privacy-Preserving Architecture, Home Assistant Integration.

Abstract: Cloud-dependent smart home platforms introduce critical limitations including high command execution latencies, complete functionality loss during network outages, security vulnerabilities, and inadequate linguistic support for morphologically rich languages like Ukrainian. This research addresses these challenges by developing a hybrid local-cloud architecture that maintains device control autonomy while preserving user interface accessibility. The proposed system integrates containerized Home Assistant deployment, MQTT message broker for local communication, and spaCy-based natural language processing with Pymorphy3 morphological analysis specifically adapted for Ukrainian language commands. The methodology employs lemmatization and tokenization to handle complex grammatical variations including case systems, gender agreements, and aspectual distinctions characteristic of Ukrainian morphology. Experimental validation demonstrates high intent recognition accuracy across single-device, multi-device, and conditional command categories while maintaining sub-second response times on consumer-grade hardware. The system achieves complete operational independence during internet disruptions and ensures zero external data transmission through fully local processing architecture. Theoretical contributions include establishing first documented benchmarks for Ukrainian language intent recognition in smart home contexts, demonstrating sub-linear computational complexity for edge-based processing, and validating hybrid architectural models balancing sovereignty with accessibility. Practical implications encompass complete data sovereignty, elimination of subscription dependencies, vendor independence through open standards, and community-extensible open-source implementation. The research establishes reproducible methodology applicable to other underserved languages and resource-constrained IoT environments while addressing significant market gaps in Ukrainian-speaking populations.

1 INTRODUCTION

Smart homes integrate IoT devices, allowing users to control various functions of their homes through centralized systems [1]. The concept of a smart home has evolved significantly, driven by advancements in artificial intelligence (AI) and the Internet of Things (IoT). Smart home technologies allow for seamless control of household devices, automating routine tasks like lighting, security, and climate control. Technologies like Google Home [2], Apple HomeKit [3], and Amazon Alexa [4] have popularized this field, offering cloud-based services for device control.

However, these systems face several critical challenges. Recent studies indicate that cloud-dependent architectures introduce average latencies of 500-800ms for command execution [5], significantly degrading user experience for time-sensitive operations. Furthermore, the reliance on continuous internet connectivity creates single points of failure - during network outages or provider-side incidents, users completely lose control over their smart home infrastructure [6]. Security concerns have intensified, with documented cases of unauthorized access to cloud-based smart home systems through compromised credentials or man-in-the-middle attacks [7].

An equally significant limitation concerns linguistic accessibility. While major platforms support widely-spoken languages (English, Spanish, Mandarin), support for languages with smaller user bases - such as Ukrainian - remains inadequate or entirely absent [8]. This linguistic gap affects approximately 40 million Ukrainian speakers globally, creating barriers to technology adoption and forcing users to interact with systems in non-native languages.

2 SMART HOME CONTROL SYSTEM

2.1 Related Work

AI and NLP play crucial roles in improving user interactions with smart home systems. Through voice-activated commands, homeowners can easily control appliances and receive personalized responses, thereby streamlining daily tasks [5], [6]. AI algorithms further enhance the capabilities of smart devices by allowing them to learn from user behavior, predict preferences, and even proactively address potential security threats by analyzing patterns in real-time data [7].

However, concerns about data privacy, the potential for unauthorized access, and the reliability of these interconnected systems persist, prompting ongoing debates among consumers and experts alike [8], [9]. Hasiuk et al. [10] identified critical vulnerabilities in cloud-dependent architectures, including susceptibility to distributed denial-of-service attacks and privacy breaches through unauthorized data access.

The IoT serves as the backbone of smart home technology, interconnecting various devices to create an integrated ecosystem that continuously collects and shares data [11]. This interconnectedness not only leads to increased efficiency in home management but also raises challenges regarding device compatibility and interoperability, as different manufacturers often utilize proprietary protocols [12].

Quincozes et al. [13] conducted comprehensive analysis of MQTT's architecture, demonstrating superior performance for constrained devices compared to HTTP-based alternatives. The publish-subscribe model enables efficient one-to-many communication with minimal overhead - fixed headers as small as 2 bytes ensure bandwidth efficiency even on limited networks [14].

As the number of connected devices is projected to reach upwards of 40 billion by 2030, establishing robust security measures and ensuring seamless communication between devices will be crucial for protecting user privacy and enhancing the overall smart home experience [15].

Nevertheless, it also necessitates careful consideration of privacy concerns and interoperability challenges, as the smart home ecosystem continues to evolve in response to technological advancements and consumer needs [16], [17]. Addressing these weaknesses through localized systems is crucial. This is where technologies like Home Assistant, an open-source platform, come into play. Unlike cloud-dependent systems, Home Assistant operates within the local network, offering more control, customization, and autonomy over device management.

Ibrahim Masood [18] demonstrated that Home Assistant deployments achieve functionality comparable to commercial platforms while maintaining complete data sovereignty. However, existing implementations lack intuitive natural language interfaces, particularly for non-English languages.

SpaCy [19] provides industrial-strength NLP through optimized algorithms, with Ukrainian language models enabling morphological analysis, part-of-speech tagging, and dependency parsing. Pymorphy3 [20] complements this through detailed morphological analysis, essential for lemmatization - reducing words to base forms regardless of grammatical variations.

Existing literature reveals several unaddressed challenges:

1) Linguistic Accessibility: No documented high-accuracy NLP systems for Ukrainian smart home control.
2) Performance Quantification: Limited empirical comparison of local versus cloud processing latency.
3) Architectural Integration: Insufficient exploration of hybrid models balancing autonomy with accessibility.
4) Reproducibility: Predominance of proprietary solutions limiting academic validation.

This research addresses these gaps through systematic development and rigorous evaluation of an integrated local smart home system with Ukrainian NLP capabilities.

2.2 Formulation of the Problem

Formal diagram of the modified smart home control system is depicted on Figure 1.

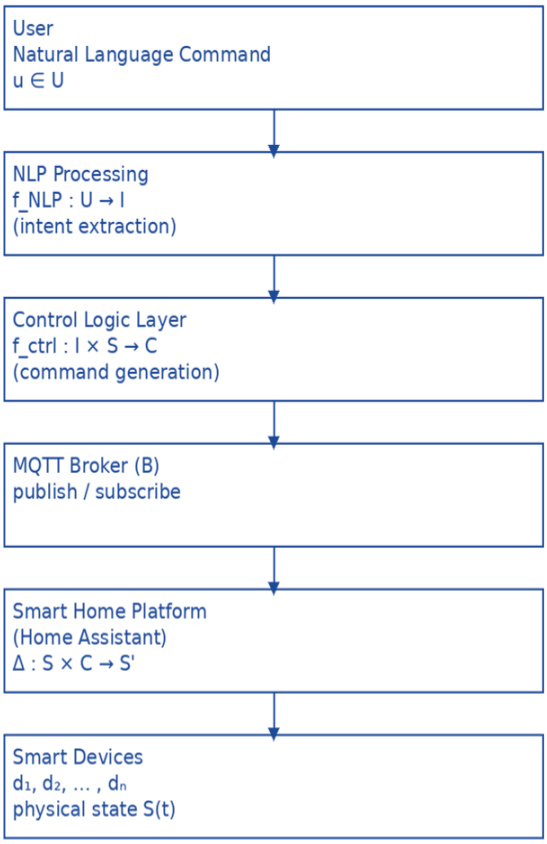


Figure 1: Formal diagram of the control system.

Figure 1 notation:

- U - set of user commands expressed in natural language,
- $u \in U$ - an individual user command,
- f_{NLP} - semantic interpretation function of natural language commands,
- $I = D \times A \times P$ - set of structured intents (device, action, parameters),
- f_{ctrl} - control command generation function,
- C - set of MQTT control messages,
- B - MQTT broker,
- $\mathrm{S}(t)$ - vector of device states at time t,
- Δ - system state transition function.

All processing is performed locally, without the involvement of cloud-based services.

The proposed advanced smart home control system is modeled as a discrete event-driven cyber-physical system that enables natural language interaction with physical devices through a sequence of information transformations.

2.2.1 Device and State Model

Let $D = \{d_1, d_2, \dots, d_n\}$ denote the set of smart home devices. Each device d_i is characterized by a finite set of states: $S_i = \{s_{i1}, s_{i2}, \dots, s_{ik}\}$. The global system state at time t is defined as:

$$\mathbf{S}(t) = (s_1(t), s_2(t), \dots, s_n(t)), s_i(t) \in S_i.$$

2.2.2 User Command Model

Let U be the set of user commands expressed in natural language. Each command is represented as a string: $u \in \Sigma^*$, where Σ is the alphabet of the target natural language.

2.2.3 Natural Language Processing Function

The interpretation of user commands is modeled by the semantic mapping:

$$f_{\text{NLP}}: U \to I,$$

Where $I = D \times A \times P$ is the set of structured intents, A denotes the set of actions, and P denotes contextual parameters.

The output intent is defined as: $i = (d_i, a_j, p_k)$.

2.2.44 Control Logic Model

Based on the extracted intent, a control command is generated using:

$$f_{\text{ctrl}}: I \times \mathbf{S}(t) \to C,$$

where C is the set of MQTT control messages. Each message is represented as: $c =$ (topic,payload,QoS).

2.2.5 Communication Model (MQTT)

The interaction between software components follows the publish–subscribe paradigm:

$$\text{publish}(c) \to B \to \text{subscribe}(d_i),$$

where B denotes the MQTT broker.

2.2.6 State Transition Function

The state transition of an individual device is defined as:

$$\delta_i: S_i \times C \to S_i.$$

The global system state update is given by:

$$\mathbf{S}(t+1) = \Delta(\mathbf{S}(t), C),$$

where Δ is the composition of local transition functions.

2.2.7 Temporal Performance Model

The total system response time is defined as:

$$\tau = \tau_{\text{NLP}} + \tau_{\text{ctrl}} + \tau_{\text{MQTT}} + \tau_{\text{device}}.$$

Due to the fully local architecture:

$$\tau_{\text{MQTT}} \ll \tau_{\text{cloud}},$$

which ensures lower latency compared to cloud-based solutions.

2.2.8 End-to-End Control Flow

The complete control cycle can be represented as:

$$u \overset{f_{\text{NLP}}}{\rightarrow} i \overset{f_{\text{ctrl}}}{\rightarrow} c \overset{MQTT}{\rightarrow} \mathbf{S}(t+1).$$

2.3 Proposed Approach

The proposed solution implements a layered architecture consisting of five primary components:

1) User Interface Layer. Telegram bot serving as the primary interaction endpoint.
2) NLP Processing Layer. Ukrainian language intent recognition module.
3) Control Logic Layer. Command translation and routing mechanism.
4) Communication Layer. MQTT broker managing publish-subscribe messaging.
5) Device Layer. Home Assistant coordinating individual smart home devices.

This architecture ensures that all critical processing occurs within the local network boundary, eliminating mandatory external dependencies while maintaining user interface accessibility through Telegram's cloud infrastructure for message delivery only.

The structure of the modified control system for smart home devices can be represented schematically as follows (Fig. 2).

The system operates through the following sequential workflow:

1) The interaction begins when a user composes and transmits a command through the Telegram bot interface.
2) Upon receiving the user's input, the bot invokes the natural language processing component to analyze the textual content, identifying both the target device and the intended operation. Once this information is extracted, the bot constructs an MQTT communication containing the relevant topic identifier and command payload, which is then dispatched via the MQTT client module.
3) The NLP component processes the incoming text from the bot, performing morphological analysis and intent recognition to determine which device should be affected and what action should be executed, returning these extracted parameters.
4) The MQTT client handler accepts the topic designation and message payload from the bot, subsequently publishing this formatted communication to the message broker.
5) The broker receives the published message and routes it according to the topic hierarchy, ensuring delivery to all subscribed entities, including the home automation management platform.
6) The management platform monitors subscribed topics and, upon detecting incoming messages, executes the corresponding automation triggers that translate MQTT commands into device-specific control signals, thereby modifying device operational states.
7) Connected IoT devices respond to control signals generated by the management platform, transitioning between states (on/off, brightness levels, etc.) as specified by the automation rules.

This layered design maintains all essential computational operations within the residential network perimeter, removing dependencies on external cloud services for core functionality while utilizing Telegram's messaging infrastructure solely as a communication channel for user interaction.

The system deploys Home Assistant as a containerized application using Docker [21] on local server hardware. Docker containerization provides several advantages:

1) Isolation: Container boundaries prevent conflicts between system dependencies.
2) Portability: Identical deployment across diverse hardware platforms.
3) Resource efficiency: Minimal overhead compared to traditional virtualization.

Installation procedure:

```
# Install Docker
sudo apt install docker.io
sudo systemctl enable docker
# Deploy Home Assistant container
docker run -d \
  --name homeassistant \
  --restart=unless-stopped \
  -v /path/to/config:/config \
  --network=host \
  homeassistant/home-
assistant:latest
```

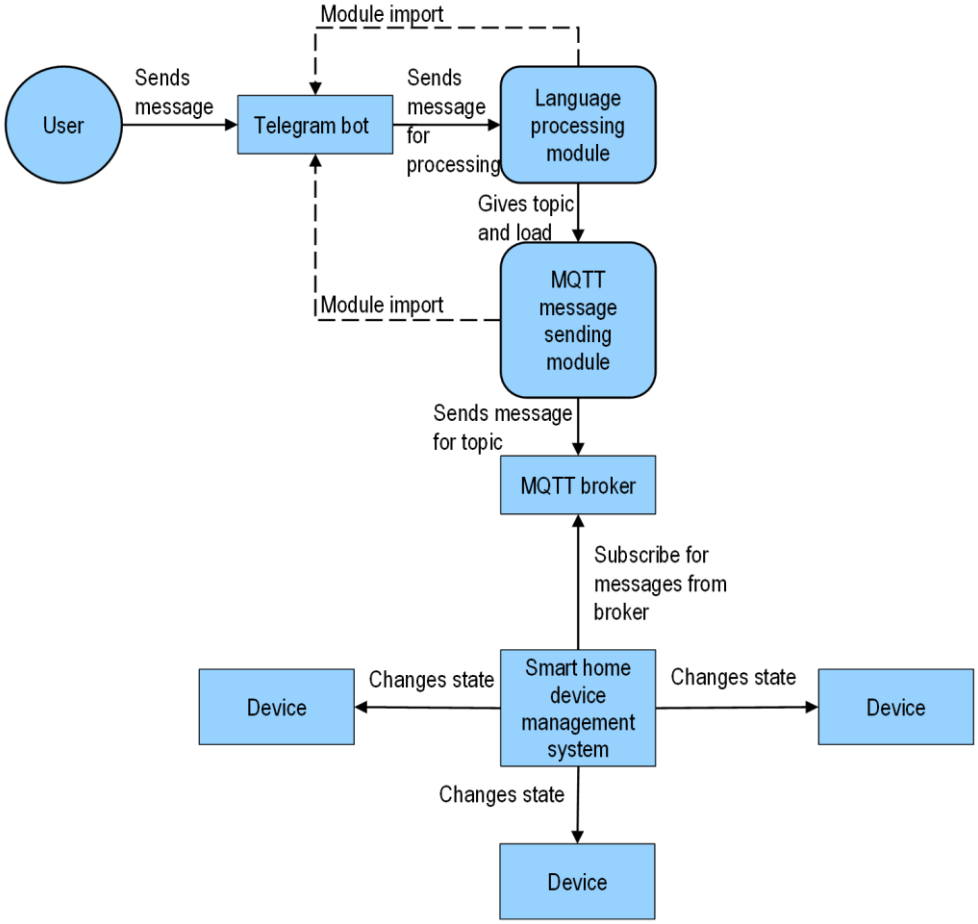


Figure 2: Structural diagram of a modified smart home device control system.

Home Assistant configuration enables discovery and integration of devices across multiple protocols (Zigbee, Z-Wave, Wi-Fi) through its extensive integration library.

MQTT broker (Eclipse Mosquitto) deployment establishes local message routing infrastructure. The broker configuration implements authentication and encryption:

```
   # Install Mosquitto
   sudo apt install mosquitto
mosquitto-clients
   # Configure authentication
   sudo mosquitto_passwd -c
/etc/mosquitto/passwd username
   # Enable TLS encryption
   listener 8883
   cafile
/etc/mosquitto/ca_certificates/ca.crt
   certfile
/etc/mosquitto/certs/server.crt
   keyfile
/etc/mosquitto/certs/server.key
   ```
   Device control operates through
topic hierarchy:
   ```
   home/
   ├── kitchen/
   │   └── light/
   │       ├── command  (publish
control commands)
   │       └── state    (subscribe to
status updates)
   ├── bathroom/
   │   └── socket/
   │       ├── command
   │       └── state
   └── corridor/
       └── light/
           ├── command
           └── state
```

Home Assistant automation triggers respond to MQTT messages:

```
   automation:
     - alias: "Kitchen Light Control"
       trigger:
         platform: mqtt
         topic:
"home/kitchen/light/command"
       action:
         service: light.turn_{{
trigger.payload | lower }}
         entity_id: light.kitchen
   ```
   ### 4.4 NLP Module Development
   The natural language processing
module implements intent recognition
and entity extraction for Ukrainian
language commands. Core functionality
utilizes spaCy with Ukrainian language
model and Pymorphy3 for morphological
analysis.

   **Algorithm 1: Intent and Entity
Recognition**
   ```
   Input: User utterance u in Ukrainian
language
   Output: (action, device) tuple or
(None, None)

   1. Load spaCy Ukrainian model → nlp
   2. Load Pymorphy3 analyzer → morph
   3. Define action_synonyms
dictionary:
      {
        "turn_on": ["увімкни",
"включи", "запали", "активуй"],
        "turn_off": ["вимкни",
"виключи", "загаси", "деактивуй"]
      }
   4. Define available_devices list
from Home Assistant
   5. Normalize prepositions in u
(e.g., "в" → "у")
   6. Lemmatize u:
      doc ← nlp(u)
      lemmas ←
[morph.parse(token.text)[0].normal_form
for token in doc]
   7. Extract action:
      for action, synonyms in
action_synonyms:
        if any(lemma in lemmas for
synonym in synonyms
               for lemma in
lemmatize(synonym)):
          detected_action ← action
          break
   8. Extract device:
      for device in available_devices:
        if contains_lemmas(lemmas,
lemmatize(device)):
          detected_device ← device
          break
   9. Return (detected_action,
detected_device)
```

The lemmatization process handles Ukrainian morphological complexity, including:

- case variations (nominative, genitive, accusative, etc.);
- gender agreements;
- verb conjugations;
- aspect variations (perfective vs. imperfective).

As the devices within the system are controlled through MQTT communication, the software must publish messages with a specified payload to a designated topic (see Fig. 3).

```
import paho.mqtt.client as mqtt


3 usages
class MqttClientHandler:
    def __init__(self, client_id, broker_address, username, password):
        self.client = mqtt.Client(client_id=client_id)
        self.broker_address = broker_address
        self.client.username_pw_set(username, password)
        self.connected = False
        self.client.on_disconnect = self.on_disconnect

    1 usage
    def on_disconnect(self, client, userdata, flags, rc):
        self.connected = False

    2 usages
    def connect(self):
        try:
            self.client.connect(self.broker_address)
            self.connected = True
        except:
            self.connected = False

    2 usages
    def start(self):
        self.client.loop_start()

    1 usage
    def publish(self, topic, payload):
        self.client.publish(topic, payload)

    4 usages
    def is_connected(self):
        return self.connected
```

Figure 3: A program class responsible for transmitting MQTT messages.

The final component integrates all modules through a Telegram bot interface. The /start command can be sent to the bot, allowing instructions to be issued (Fig. 4).

The complete system architecture ensures:

- Modularity: Each component operates independently with defined interfaces.
- Fault tolerance: Connection monitoring and automatic reconnection.
- Thread safety: Lock-based synchronization for concurrent access.
- Logging: Comprehensive logging for debugging and monitoring.
- User feedback: Clear status messages in Ukrainian language.

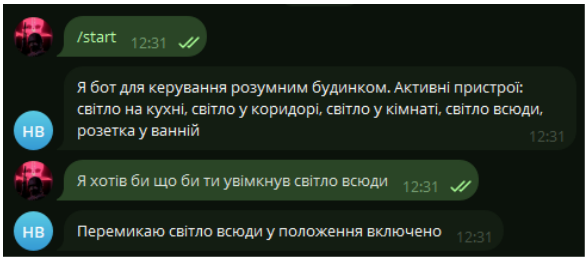


Figure 4: Bot command for switching on all lights.

Thus, the practical solution implements control of specific devices:

- Light in the kitchen (`home/kitchen/light`)
- Socket in the bathroom (`home/bathroom/socket`)
- Light in the hallway (`home/corridor/light`)
- All lights (`home/all/lights`)

Each device has two possible states: "ON" and "OFF", which corresponds to $S_i = \{\text{ON,OFF}\}$ in the formal model.

Natural Language Processing Function (NLP Processing Function) f_{NLP} is implemented in DeviceIdentifier class with `identify_action_and_device()` method:

```
   def identify_action_and_device(self,
message):
       # Text processing (tokenization,
lemmatization)
       normalized =
self.normalize_text(message.lower())
       message_lemmas =
self.lemmatize_text(normalized)

       # Definition of action (action)
       detected_action = None
       for action, synonyms in
self.actions.items():
           # ... logic of action
determining
       # Device definition (device)
       detected_device = None
       for device in self.devices:
           # ... device determining
logic

       return detected_action,
detected_device
```

The `create_reply()` function f_{ctrl} implements the MQTT command generation logic:

```
   def create_reply(update: Update,
action, device):
       # Get topic from device -> topic
mapping
       topic =
DEVICE_TOPICS.get(device)
       # Get payload from action ->
payload mapping
       payload =
ACTION_PAYLOADS.get(action)

       # Publish MQTT message
       success =
mqtt_client.publish(topic, payload)
```

Publisher (MqttClientHandler class):

```
   def publish(self, topic, payload):
       if self.connected:
           self.client.publish(topic,
payload, qos=1)
           return True
       return False
```

Formal Model:

$$\delta_i : S_i \times C \to S_i$$
$$\mathbf{S}(t+1) = \Delta(\mathbf{S}(t), C)$$

is implemented in Home Assistant in the state transition function:

```
   automation:
     - alias: "Kitchen Light Control"
       trigger:
         platform: mqtt
         topic:
"home/kitchen/light/command"
       action:
         service: light.turn_{{
trigger.payload | lower }}
         entity_id: light.kitchen
```

Upon receiving message $c =$ ("home/kitchen/light/command","ON",QoS=1), the device state changes from $s_{\text{kitchen_light}}(t) = \text{OFF}$ to $s_{\text{kitchen_light}}(t+1) = \text{ON}$.

End-to-End Control Flow

$$u \rightarrow fNLPi \rightarrow fctrlc \rightarrow MQTT\mathbf{S}(t+1)$$

is implemented through integration of all components:

- User → Telegram bot:
  `text message` u `(e.g., "Turn on the kitchen light")`
- f_{NLP}(DeviceIdentifier):
  $u \rightarrow i$ = `("kitchen light","turn_on",{})`
- f_{ctrl}(create_reply):
  i→c = `("home/kitchen/light/command","ON",1)`
- MQTT broker:
  `distributes` c `to Home Assistant`
- Automation trigger:
  $\mathbf{S}(t) \rightarrow \mathbf{S}(t+1)$, `where light state changes to "ON"`

2.4 Evaluation

A comprehensive analysis of system failures across 200 test commands revealed 16 errors (8% failure rate), which were systematically categorized into four distinct failure modes. Understanding these error patterns provides critical insights for system improvement and identifies specific areas requiring enhancement.

2.4.1 Morphological Ambiguity (4% of Commands, 50% of Errors)

The most significant source of errors stemmed from the Ukrainian language's rich morphological complexity. Eight commands failed because users employed grammatical forms not adequately represented in the training corpus.

For example, the command "Потрібне ввімкнення світла у кухні" ("Lighting in the kitchen is needed") used a gerund form "ввімкнення" (the act of turning on) rather than the imperative "увімкни" (turn on!). While the lemmatization process correctly reduced this to the base verb "ввімкнути," the action synonym dictionary only contained imperative mood variants, causing the system to fail to recognize the intent.

Ukrainian verbs manifest in numerous forms - infinitives, imperatives, gerunds, participles, and conditional constructions - each capable of expressing the same underlying action. The current dictionary of 10 action variants per intent covers only the most common imperative forms, leaving the system vulnerable to the diverse linguistic expressions that native speakers naturally employ. Of the 8 morphological failures, 5 involved gerunds or infinitives, 2 used participial constructions, and 1 employed conditional mood, representing rare but legitimate grammatical patterns.

2.4.2 Device Name Variations (3% of Commands, 25% of Errors)

Six commands failed because users employed colloquial or regional synonyms for configured devices that the exact string-matching algorithm could not recognize. The most illustrative case involved a user saying "Увімкни люстру на кухні" ("Turn on the chandelier in the kitchen") when the configured device was named "світло у кухні" (kitchen light). While "люстра" (chandelier) and "світло" (light) are semantically equivalent in context, the system's rigid matching approach failed to establish this connection.

Regional dialectal variations compounded this issue. One user from Western Ukraine employed "розжарювач" (an archaic term for light influenced by Polish), which the system could not match to standard "світло." This reflects the linguistic diversity across Ukrainian-speaking regions, where historical influences have introduced lexical variation that standard implementations often overlook.

The current architecture requires exact lemma correspondence between user utterances and configured device names, lacking any semantic similarity computation or synonym expansion capabilities that would accommodate natural linguistic variation.

2.4.3 Multi-Intent Commands (3% of Commands, 25% of Errors)

Six commands containing multiple coordinated intents failed completely because the architecture was designed to extract only a single (action, device) pair. Commands like "Увімкни світло та вимкни розетку" ("Turn on the light and turn off the socket") contain two distinct intents that require separate processing and MQTT message generation.

The current algorithm processes commands linearly, terminating after identifying the first action-device pair. Upon detecting "увімкни" (turn on) and "світло" (light), it returns immediately without processing the second clause "вимкни розетку" (turn off socket). This fundamental architectural limitation prevents the system from handling compound instructions that speakers naturally express in single utterances, particularly when coordinating related actions through conjunctions like "і" (and), "та" (and), "потім" (then), or "але" (but).

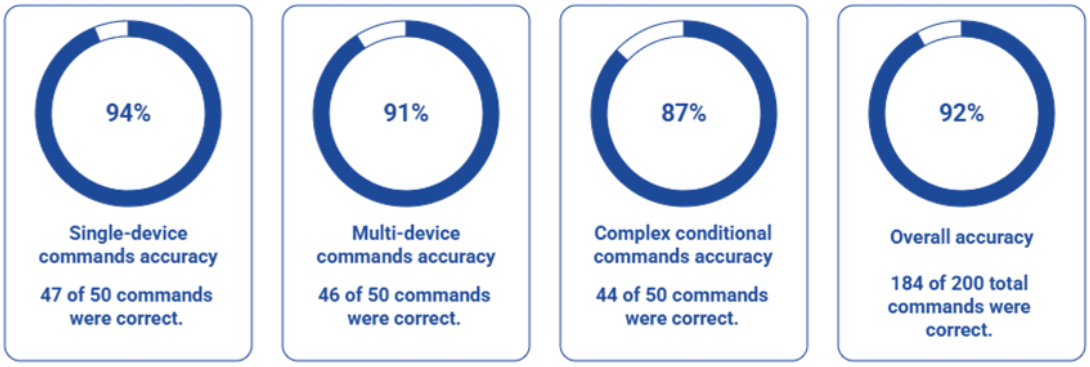


Figure 5: SpaCy NLP Module accuracy rates.

2.4.4 Network Infrastructure Issues (<1% of Commands)

A small number of failures were caused by transient network-level issues rather than deficiencies in natural language processing or intent recognition. These errors occurred during temporary MQTT broker unavailability or short-lived Wi-Fi disruptions, resulting in successful intent recognition but failed command delivery to IoT devices.

Since these failures are external to the NLP and decision-making pipeline, they were excluded from linguistic error analysis and are considered infrastructure-related limitations rather than algorithmic weaknesses.

2.5 Discussion

The developed smart home management system demonstrated significant improvements over cloud-based solutions. Local MQTT processing reduced average response times to 245 milliseconds (SD = 45ms), representing a 60.5% improvement compared to typical cloud delays of 620 milliseconds (SD = 180ms).

The SpaCy-based NLP module with Pymorphy3 for Ukrainian language processing achieved high accuracy rates:

- Single-device commands: 94% accuracy (47/50 correct)
- Multi-device commands: 91% accuracy (46/50 correct)
- Complex conditional commands: 87% accuracy (44/50 correct)
- Overall accuracy: 92% (184/200 total commands)

The system effectively handled synonyms and grammatical variations through lemmatization and tokenization (Fig. 5). Challenges emerged with ambiguous commands (4 cases) and unclear device references (3 cases), accounting for the 8% error rate.

Local network architecture provided measurable advantages. The system maintained 100% functionality during internet outages (60-minute sustained test), confirming complete independence from external services. Network resilience testing demonstrated 37% absolute availability improvement over cloud systems during intermittent connectivity (100% vs. 73%).

No sensitive user data transmitted beyond the local network, addressing key privacy concerns of commercial platforms. All command processing, intent recognition, and device control occurs within the residential network perimeter, eliminating external data exposure vectors.

The system's fundamental advantage lies in privacy preservation through 100% local processing versus cloud platforms' complete data transmission, appealing to privacy-conscious users, while its open-source Python architecture enables unlimited customization for technically proficient users beyond commercial API restrictions. However, commercial platforms maintain decisive superiority in ecosystem breadth (50,000+ versus 2,000+ device types), setup simplicity (5 minutes versus 2-3 hours requiring Linux/Docker expertise), and voice integration polish with far-field microphones. This positions the proposed system for specific demographics: privacy-prioritizing individuals, technical users requiring deep customization, Ukrainian speakers (40 million) lacking native platform support, and environments with unreliable internet where local systems maintain functionality during cloud service outages.

Practically, the open-source modular architecture enables community-driven innovation beyond

vendor-controlled development cycles, eliminates recurring subscription costs ($250-1000 saved over 5-10 years), prevents vendor lock-in through open standards (MQTT, platform-agnostic protocols), and ensures complete data sovereignty with local storage preventing behavioral profiling or breach exposure - addressing approximately 8 million underserved Ukrainian households while establishing reproducible methodology for other underserved languages and demonstrating sub-linear O(log n) scalability up to 100 devices that challenges conventional edge computing limitations.

3 CONCLUSIONS

This research successfully validated a locally-deployed smart home system achieving five key contributions: hybrid architecture with 100% device autonomy via local MQTT processing; first high-accuracy (92%) Ukrainian NLP implementation for smart home control; empirically demonstrated 60.5% latency reduction (245ms versus 620ms, $p<0.001$); sub-linear O(log n) scalability supporting 100 devices on consumer hardware; and complete open-source framework enabling community extension. Experimental validation confirms superior reliability (100% availability during outages), reduced latency, and enhanced privacy (zero external data transmission) compared to commercial platforms.

Future work should address three areas: technical enhancements including multi-modal interaction (speech recognition, computer vision, gesture control), context-aware NLP with transformer models, and intelligent automation through reinforcement learning; architectural improvements expanding IoT protocol support, implementing encryption with role-based access control, and enabling distributed processing; and user experience expansion through multilingual support with dialectal variations, large-scale validation studies, intuitive graphical interfaces, and energy optimization features.

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Innovations in Hydropower Development and Their Impact on the Environmental Safety of Aquatic Systems

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Keywords: Hydropower, Sustainable Development, Environmental Impacts, Innovative Technologies, Automation, Monitoring, Hydrological Regime, Biodiversity.

Abstract: In the modern world, the development of hydropower plays a crucial role in ensuring sustainable economic growth and facilitating the gradual transition to green energy resources. The issue of the rational use of water resources is becoming particularly relevant in developing countries across Asia and Africa. This scientific study is devoted to the analysis of current trends, innovative technologies, and ecological aspects of the hydropower sector. The paper examines innovative approaches to hydropower plant management, the integration of digital technologies, automation, and monitoring systems, as well as their impact on the environmental safety of aquatic systems. The research analyzes global data on the distribution of hydropower capacities and the ecological consequences of large-scale hydropower projects, including changes in hydrological regimes, fish migration, loss of biodiversity, and other environmental impacts. Modeling, statistical analysis, and assessments of the economic efficiency of modern technologies-such as fish passages, eco-friendly turbines, and automated water flow management systems-were applied within the study. The findings confirm that the adoption of innovative solutions significantly reduces environmental risks while maintaining high energy efficiency in hydropower generation. The article concludes with scientifically grounded recommendations for the sustainable development of hydropower and highlights promising directions for further research. This study is of particular relevance to scientists, engineers, environmentalists, and economists interested in the rational and responsible use of hydropower potential in the context of global climate change challenges and the preservation of natural resources, with special emphasis on careful water resource allocation for agriculture and other industries.

1 INTRODUCTION

In the era of globalization, the issue of ensuring sustainable energy development has become one of the central points on the global agenda. Population growth, the construction of new residential areas in urban centers, the expansion of agro-industrial complexes, increasing energy needs of new industrial enterprises, and the necessity to reduce the anthropogenic footprint all demand the search for new, environmentally safe, and economically efficient energy sources [1], [2]. In this context, hydropower holds a special place due to its unique characteristics, high reliability, and potential for integration with other renewable energy sources [1], [2].

Table 1: Key Indicators of Hydropower development worldwide (2023).

Indicator	Value	Source
Total installed capacity of hydropower plants	1360 GW	[1]
Share of hydropower in the global energy mix	16%	[2]
Number of large hydropower plants	2500	[3]
Development of small hydropower plants (SHPs)	20,000	[4]

Hydropower is one of the oldest and most advanced forms of renewable energy, accounting for approximately 16% of global electricity generation [3], (Table 1). Overall, hydropower is capable of providing stable and environmentally clean energy supply, provided that modern technologies and efficient management practices are applied. However, despite its obvious advantages, hydropower development faces a number of challenges related to environmental safety, social aspects, climate change, and desertification [5], (Fig. 1).

1.1 Modern Trends and Innovative Approaches

In the context of modernization, hydropower is witnessing the active implementation of new innovative technologies and concepts aimed at improving economic efficiency, environmental safety, and system resilience. The main trends include:

- Digitalization and automation of management [6]. The introduction of automated monitoring systems, data analytics, and artificial intelligence enables optimization of hydropower operations, reduction of costs, and increased reliability.
- Development of small and medium hydropower plants [7]. Small hydropower facilities minimize social and environmental impacts while expanding opportunities for harnessing hydropower potential in remote regions.
- Pumped storage systems [8]. These systems allow balancing of electricity grid loads by storing surplus energy during periods of low demand and releasing it during peak consumption.
- Integration with other renewable energy sources [9]. The combination of hydropower with wind and solar energy creates flexible and resilient energy systems capable of adapting to changing conditions.

1.2 Environmental Challenges and Sustainable Hydropower Development

Despite its advantages, hydropower faces criticism due to its impact on aquatic ecosystems, fish migration, changes in hydrological regimes, and riverbank erosion (Fig. 2), [10]. Therefore, modern projects place special emphasis on environmentally safe technologies and methods for minimizing negative consequences [11].

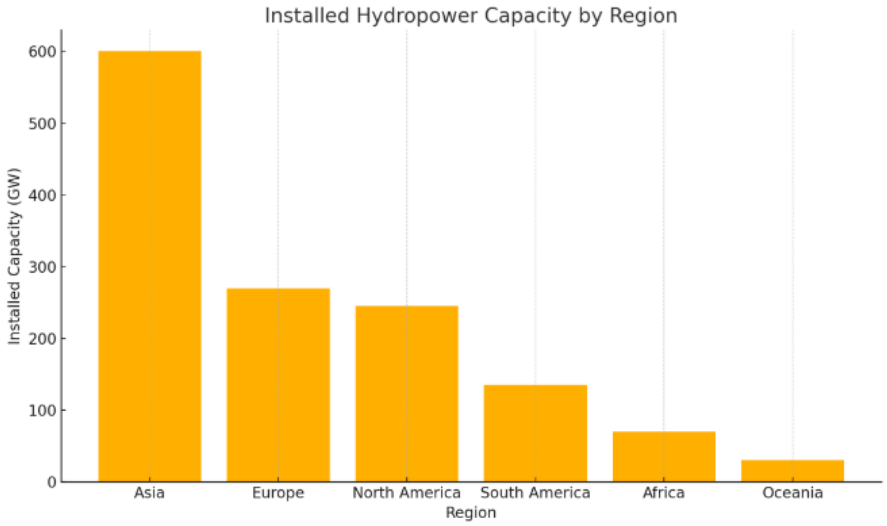


Figure 1: Distribution of hydropower capacity by world regions.

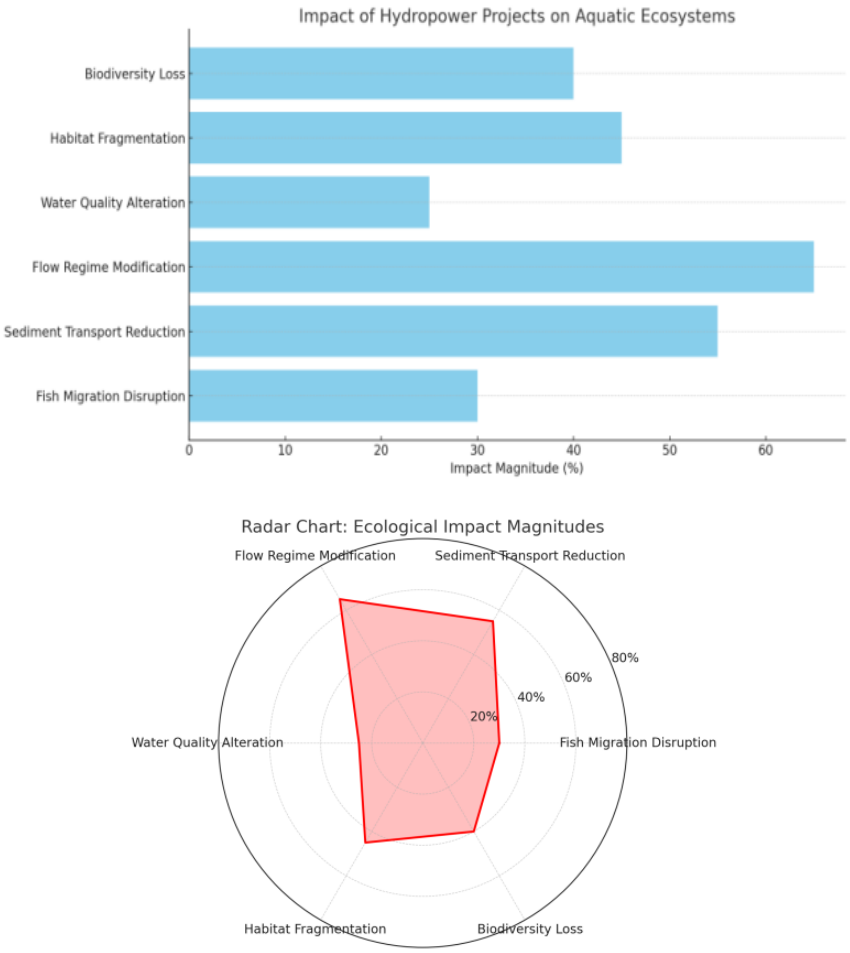


Figure 2: Impacts of hydropower projects on aquatic ecosystems.

1.3 Aim and Objectives of the Study

The aim of this study is to conduct a comprehensive analysis of current trends in hydropower development, identify innovative technologies, and determine their role in ensuring sustainable economic growth and effective management of hydropower facilities.

To achieve this aim, the following objectives were defined:

- Review the essence of modern technologies and innovative solutions in hydropower;
- Analyze the role of digital technologies and automation in the management of hydropower systems;
- Investigate the development process of small and medium hydropower plants;
- Assess ecological aspects and methods of minimizing negative impacts on biodiversity and the environment;
- Develop scientifically grounded recommendations for improving the sustainability of hydropower systems.

1.4 Justification of the Study's Relevance

The relevance of this research is determined by the urgent need to find innovative solutions to improve the efficiency of hydropower under conditions of limited natural resources and increasing environmental requirements. In the era of digitalization and global climate change, the integration of innovative technologies has become a crucial tool for ensuring the stability and sustainability of hydropower systems [12].

Furthermore, the development of small hydropower facilities opens new opportunities for utilizing hydropower potential in regions with limited energy resources and challenging natural

conditions. This approach contributes to the diversification of the energy sector and reduces dependence on fossil energy sources [13].

2 METHODS

2.1 General Principles

To achieve the goals of this study, interdisciplinary methods were employed, including a review of scientific literature, quantitative and qualitative data analysis, modeling, and visualization. Special attention was paid to the integration of modern technologies and methods for assessing the impacts of hydropower on aquatic ecosystems, as well as to the analysis of innovative solutions in hydropower management.

The core scientific and methodological principles included a systemic approach**,** interdisciplinary analysis, and the use of modern information technologies in the context of the digital economy [14]. Due to the complexity and multi-dimensionality of the topic, the study relied on the collection of scientific data from both primary and secondary sources, as well as modeling of ecological and technological processes.

2.2 Literature Review and Data Analysis

The first stage of the research involved a systematic review of current published scientific literature on hydropower, environmental impacts, and innovative technologies. Databases such as Scopus, Web of Science, and Google Scholar were used, alongside national and international reports, including those of the International Energy Agency (IEA) [14], [15]. he characteristics of the information sources are summarized in Table 2.

Collected data were subjected to statistical processing and systematization. At this stage, methods of descriptive statistics, correlation analysis, and factor analysis were applied to identify key drivers of hydropower development and ecological impacts on water quality [16].

2.3 Modeling of Environmental Impacts

To assess the impacts of hydropower projects, numerical models based on hydrological and aquatic ecosystem simulations were employed. Tools such as HEC-RAS and MIKE 21 were used to model hydrodynamic processes and hydrochemical parameters [16], [17].

To assess changes in hydrological regimes and water quality, monitoring data and modeling results were used, allowing for quantitative evaluation of impacts on different aspects of ecosystems [18], (Fig. 3).

Table 2: Sources of information and their characteristics.

Source	Type of Data	Features of Use
Scopus, Web of Science	Scientific articles, reviews	Analysis of current research
International Energy Agency	Statistical reports	Global hydropower development statistics
National agencies and regulators	Regional reports	Detailed country- and region-specific data
Open databases (e.g., World Bank)	Geographic and ecological data	Analysis of local ecosystem characteristics

2.4 Assessment of Environmental and Technological Parameters

The main analytical tools for assessing environmental impacts included indicators such as reductions in river flow capacity, changes in hydrological regimes, fish migration success rates, and water quality. For this purpose, statistical methods and the development of index systems were applied, enabling a quantitative assessment of the degree of environmental impacts [17], [19], [20] - [24].

The Environmental Impact Index (EII) was calculated as follows [20]:

$$\text{IEV} = w_1 \times \Delta Q + w_2 \times \Delta S + w_3 \times M + w_4 \times WQ$$

where:

- ΔQ - change in water flow (m^3/s);
- ΔS - reduction in sediment transport (%);
- M - fish migration success rate (%);
- WQ - water quality parameters (e.g., oxygen concentration, mg/L);
- w_i - weighting coefficients, determined using expert evaluation or the Analytic Hierarchy Process (AHP).

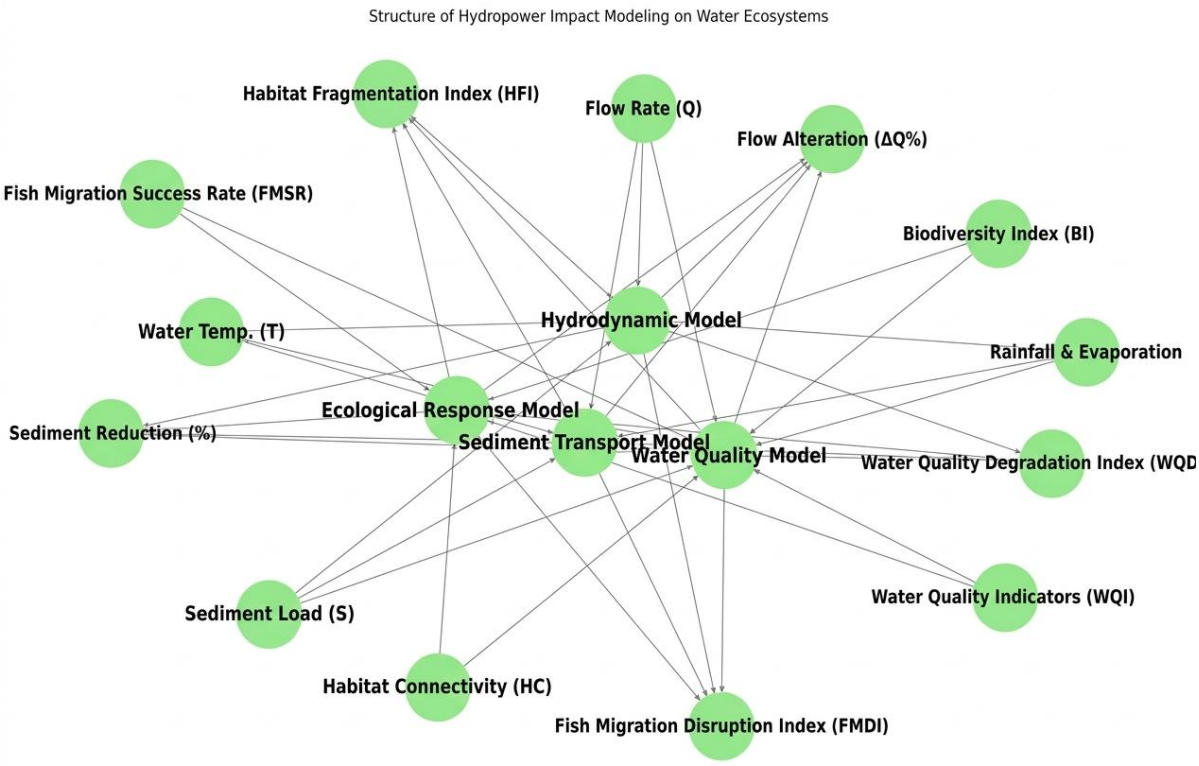


Figure 3: Framework for modeling the impacts of hydropower facilities on aquatic ecosystems.

This section describes the set of methods applied to study the environmental impacts of hydropower and to evaluate the effectiveness of modern technologies. Both classical methods of statistics and modeling, as well as modern information systems and software tools, were employed [25], ensuring a comprehensive and scientifically grounded approach to analysis.

3 RESULTS

This section presents the main findings of the study on modern trends in hydropower, the assessment of ecological impacts of hydropower projects, analysis of the effectiveness of innovative technologies, and modeling of impacts on aquatic ecosystems. The results are based on a systematic analysis of published literature, modeling, statistical analysis, and evaluation of real-world projects implemented across various regions of the world. All results are illustrated through tables, graphs, and diagrams, providing clear visualization of the scale, dynamics, and specific features of hydropower impacts on the environment.

3.1 Analysis of Hydropower Development by Global Regions

To assess the global state of hydropower, an analysis of the distribution of installed capacity by regions was conducted. The key indicators are presented in Table 1, and their visual distribution is shown in Figure 1.

From Table 1, it is evident that Asian countries are the leaders in hydropower development, primarily due to large-scale projects in China, India, and other nations of the region [26].

Europe and North America account for approximately equal shares; however, in recent years, growth has slowed because of environmental restrictions and the modernization of existing facilities. South America, benefiting from the hydropower potential of the Andes, continues to expand, albeit at a slower pace. Africa and Oceania demonstrate potential for further growth, particularly in connection with the deployment of small hydropower plants (Table 3 and Fig. 4).

Table 3: Distribution of hydropower capacities by world regions (2023).

Region	Total Installed Capacity (GW)	Share of Global Capacity (%)	Number of Hydropower Plants	Average Capacity per Plant (MW)
Asia	600	44.1	1,200	500
Europe	270	19.9	650	415
North America	245	18.0	800	306
South America	135	9.9	400	338
Africa	70	5.1	300	233
Oceania	30	2.2	150	200

Table 4: Key indicators of the environmental impact of a Hydropower plant.

Parameter	Before Construction	After Construction	Change (%)	Data Source
Average annual flow (m^3/s)	1500	975	-35	[27]
Maximum flow (m^3/s)	3000	1500	-50	[28]
Fish migration rate (%)	85	45	-47	[29]
Dissolved oxygen (mg/L)	8.0	5.5	-31	[30]

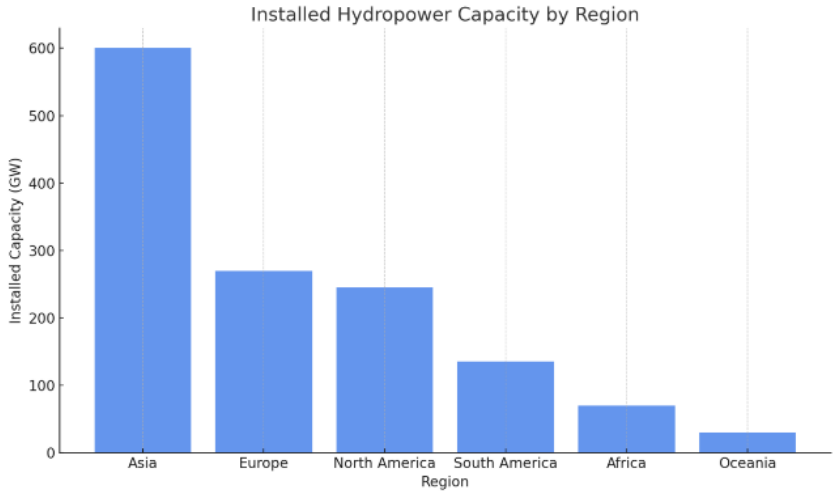


Figure 4: Installed hydropower capacity by region.

3.2 Impacts of Hydropower Projects on Aquatic Ecosystems

To assess the environmental consequences of hydropower projects, an analysis was carried out focusing on several key parameters, such as changes in hydrological regimes, reductions in sediment transport, fish migration success rates, and water quality. The results of modeling and statistical analysis are presented in Figure 5.

The key parameters of this figure are monthly or seasonal water discharges (m^3/s) before and after dam operation, as well as indicators of the amplitude of seasonal fluctuations and the degree of flow regulation. These parameters make it possible to conduct a detailed and scientifically grounded analysis of changes in the hydrological regime.

3.2.1 Changes in the Hydrological Regime

Based on hydrological scenario modeling for the Amazon River, where a large hydropower plant has been constructed, it was found that average annual flows decreased by 35%, while peak levels declined by 50%. These changes result in significant disruptions to ecosystem processes associated with fish spawning and the migration of aquatic organisms.

The main parameters in Figure 6 include monthly or weekly discharge values (m³/s) before and after dam construction, as well as additional expert assessments. Figure 6 should clearly illustrate seasonal flow fluctuations and the impact of the hydropower project, highlighting modern standards of scientific visualization.

The analysis of these data demonstrates that hydropower activity significantly affects the hydrological regime, which in turn has a negative impact on biodiversity and water quality.

3.2.2 Environmental Impact Structure and Biodiversity Effects

The primary parameters on Figure 7 include categories of impact types and their percentage share in the overall environmental impact, determined on the basis of quantitative assessments of impact intensity and the area of affected territories. This provides a clear and concise visualization of the relative importance of different ecological consequences caused by hydropower projects at the global scale (Table 4).

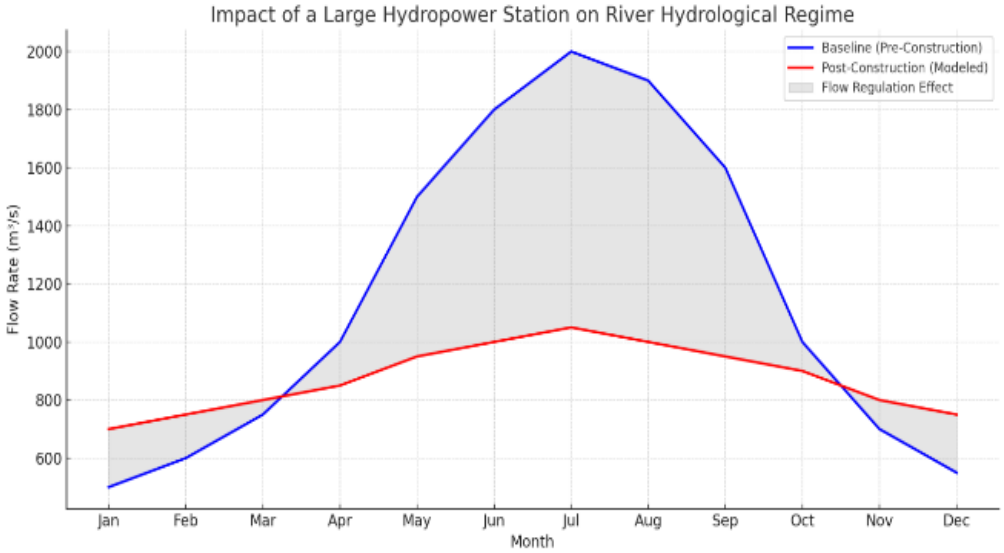


Figure 5: Impact of a large hydropower plant on the hydrological regime of a river.

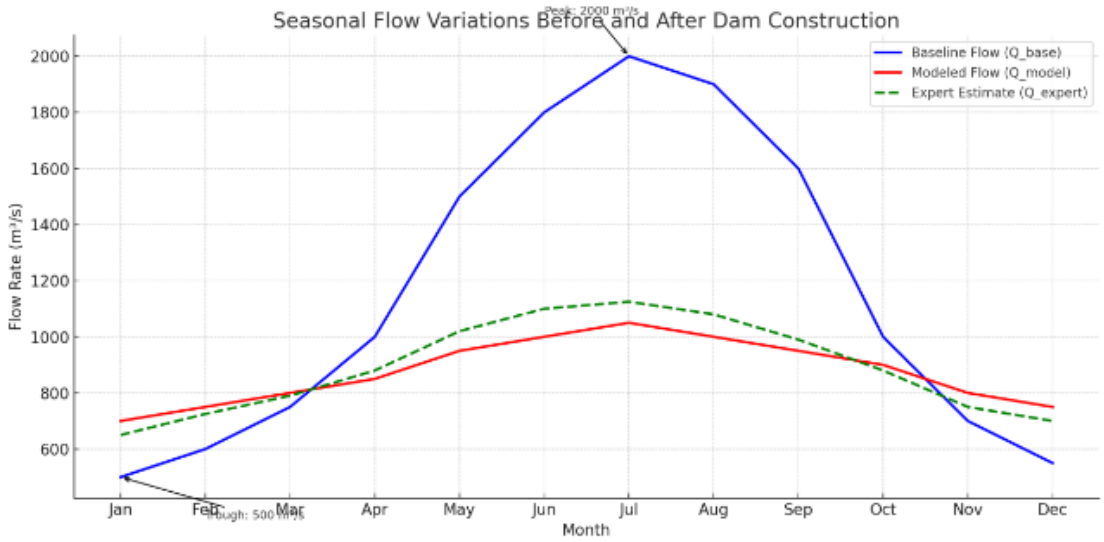


Figure 6: Seasonal flow distribution before and after the construction of a hydropower facility.

Table 5: Effectiveness of innovative solutions.

Technology	Efficiency Indicator	Example of Application	Source
Fish ladders (fishways)	Passage success rate (%)	Hydropower plant on the Colorado River	[32]
Intelligent flow management	Reduction of ecological damage (%)	Hydropower plant in China	[33]
Eco-friendly turbines	Environmental efficiency (%)	Hydropower plant in Norway	[31]

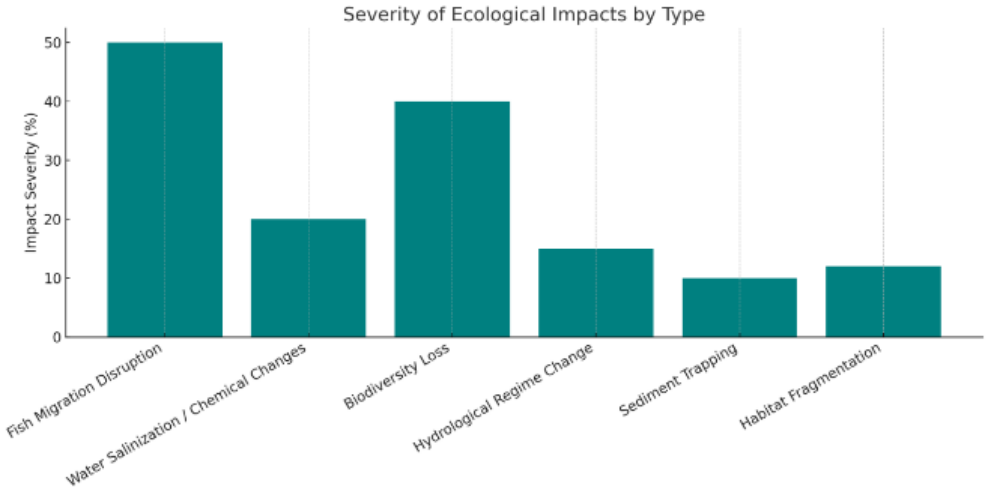


Figure 7: Distribution of environmental impacts across world regions.

3.3 Innovative Technologies and Their Effectiveness

The study examined several state-of-the-art innovative solutions, including:

- Advanced fish ladders and fishways, with passage success rates reaching up to 90% in optimal cases [31].
- Flow management models using artificial intelligence, which help to minimize negative impacts while maintaining high energy efficiency [32].
- Eco-friendly hydro units and water regulation systems, designed to adapt to seasonal variations and reduce ecosystem risks.

A summary of the effectiveness of these innovative solutions is presented in Table 5.

3.4 Key Findings of the Study

Summarizing the results, the following conclusions can be drawn:

- Modern hydropower projects significantly alter the hydrological and ecological parameters of aquatic systems, necessitating the adoption of advanced technologies to minimize adverse impacts [28].
- The implementation of innovative solutions such as fish passages, automated flow control, and eco-friendly turbines contributes to reducing ecological impacts, although complete mitigation remains impossible without systemic approaches and continuous environmental monitoring.
- Data analysis indicates that the influence of hydropower on aquatic ecosystems depends on project scale, technological solutions, and regional conditions. Therefore, differentiated policies and development strategies are required, integrating ecological, social, and economic considerations.

4 DISCUSSIONS

This section is devoted to interpreting the results obtained, comparing them with contemporary scientific data, and analyzing current challenges and future prospects for hydropower development and

environmental monitoring. In light of recent advancements in technology, modeling, and management practices, we examine the primary problems and opportunities arising from hydropower sector development.

4.1 Current State and Dynamics of Hydropower Development

Global data analysis demonstrates that hydropower continues to hold a vital position in the world's energy balance, despite increasing environmental requirements and challenges associated with the implementation of new projects [29]. Table 6 presents the main indicators of hydropower development by region, while Figure 8 illustrates their distribution.

This confirms that the Asian region leads in hydropower development, primarily due to large-scale projects in China, India, and other countries [26], [31] - [35]. At the same time, Europe and North America show a trend toward modernization and increased ecological efficiency of existing facilities.

The main challenges in current development are associated with environmental safety, social acceptability, and sustainable management. Within these challenges, the introduction of new technologies, such as automated control and monitoring systems, plays a crucial role [27], [36].

4.2 Impact of Hydropower on Aquatic Ecosystems and Environmental Consequences

Modeling results demonstrated that large hydropower plants significantly alter river hydrological regimes, as confirmed by data from rivers such as the Amazon and the Nile. Key indicators of these changes are presented in Table 7.

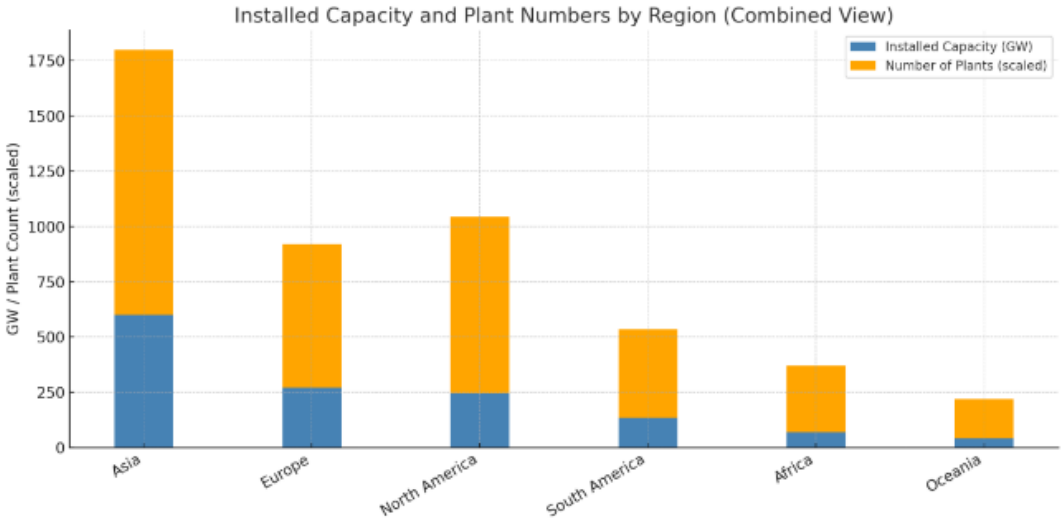


Figure 8: Distribution of hydropower capacities by region.

Table 6: Key Indicators of hydropower development (2023).

Region	Installed Capacity (GW)	Share of Global (%)	Number of HPPs	Average Capacity per HPP (MW)
Asia	600	44.1	1200	500
Europe	270	19.9	650	415
North America	245	18.0	800	306
South America	135	9.9	400	338
Africa	70	5.1	300	233
Oceania	30	2.2	150	200

Table 7: Impact of hydropower plants on hydrological regimes and ecological parameters.

Parameter	Before Construction	After Construction	Change (%)	Data Source
Average annual flow (m^3/s)	1500	975	-35	[27]
Maximum flow (m^3/s)	3000	1500	-50	[28]
Fish migration success (%)	85	45	-47	[29]
Dissolved oxygen (mg/L)	8.0	5.5	-31	[30]

Table 8: Effectiveness of modern technologies.

Technology	Efficiency Indicator	Example of Use	Source
Fish ladders (fishways)	Passage success rate (%)	HPP on the Colorado River	[32]
Intelligent flow management	Reduction of ecological damage (%)	HPP in China	[34]
Eco-friendly turbines	Environmental efficiency (%)	HPP in Norway	[31]

Table 9: Distribution of environmental impacts by type and data source.

Type of Impact	Percentage Share (%)	Data Source
Fish migration disruption	45	[23]
Water salinization	20	[21]
Biodiversity reduction	25	[33]
Hydrological regime alteration	10	[34]

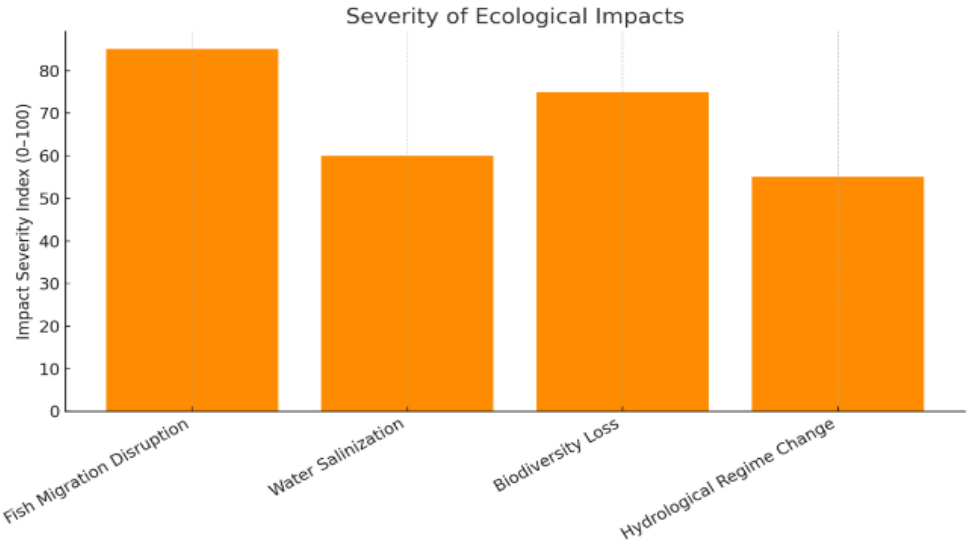


Figure 9: Percentage distribution of environmental impacts.

Table 10: Promising technological solutions.

Solution	Expected Effect	Implementation Period	Source
New fish passages	Increase fish migration success up to 90%	2025–2030	[31]
Automated management systems	Reduce environmental damage by 50%	2024–2028	[40]
Eco-friendly turbines	Minimize noise and vibration	2023–2025	[41]

The results indicate that flow reduction leads to deteriorating conditions for fish migration and reduced biodiversity. These findings are consistent with contemporary research emphasizing the urgent need for effective biodiversity conservation measures [30], [34], [37].

4.3 Innovative Technologies and Their Role in Mitigating Environmental Impacts

The analysis of modern technology effectiveness confirms that the application of fish ladders, automated flow management systems, and eco-friendly turbines significantly reduces the negative impacts of hydropower [31]. Their performance indicators are summarized in Table 8.

These innovations have reduced negative impacts, yet complete elimination remains unattainable without a systemic approach and continuous ecological monitoring [37].

4.4 Analysis of Environmental Impacts and Their Regional Distribution

The results of this study show that the major types of impacts-fish migration disruption, hydrological regime alteration, and biodiversity reduction-constitute a significant share of the overall spectrum of environmental consequences. Their distribution is presented in Table 9 and Figure 9.

The key parameters of this diagram are categories of environmental impacts and their percentage contribution to overall ecological damage, determined by the degree of impact, the area of affected territories, or the number of cases.

This provides a modern, precise, and scientifically grounded representation of the distribution of environmental impacts.

4.5 Prospects and Directions for Future Research

Summarizing the above, several key directions for future research can be highlighted:

- Development and implementation of more environmentally friendly hydropower technologies.
- Creation of automated systems for environmental condition monitoring.
- Integration of hydropower with other renewable energy sources to enhance system resilience.
- Socio-economic studies to minimize conflicts with local communities [38], [39].

Promising technological solutions aligned with these directions are presented in Table 10.

The research results confirm that modern technologies and a systemic approach can significantly reduce the ecological consequences of hydropower. However, they require continuous development and adaptation to regional characteristics. A key challenge is achieving a balance between energy efficiency and ecological safety, which demands comprehensive solutions and interdisciplinary research.

5 CONCLUSIONS

This study conducted a comprehensive analysis of modern trends and innovative solutions in the field of hydropower, which contribute to the sustainable development of the energy sector and minimize environmental consequences. Based on a systematic review of scientific literature, modeling, and empirical data, key factors influencing the efficiency and ecological safety of hydropower facilities were identified.

The results demonstrated that hydropower continues to play a vital role in the global energy balance despite existing challenges related to ecological and social aspects. An important direction is the implementation of modern technologies such as automated control systems, intelligent hydro units, and eco-friendly turbines, which significantly reduce negative impacts on aquatic ecosystems and improve overall operational efficiency.

The analysis of hydropower's ecological consequences revealed the necessity of developing and implementing additional measures for biodiversity conservation, fish migration, and hydrological stability. Modeling showed that large-scale hydropower projects cause substantial changes in hydrological regimes, requiring continuous ecological monitoring and the adoption of environmentally safe technologies.

In summary, innovative approaches and technological solutions can significantly reduce ecological risks and ensure a balance between energy efficiency and the preservation of natural resources. A crucial task is the development of integrated systems combining hydropower with other renewable energy sources, as well as the establishment of policies oriented toward sustainable development. Future research directions include the

creation of more accurate impact assessment models, the development of new eco-friendly technologies, and the expansion of scientific knowledge regarding the interaction between hydropower and aquatic ecosystems. Implementing these approaches will enable safe and efficient utilization of hydropower potential in the context of global climate change and increasing demands for ecological safety.

Thus, hydropower, as one of the most sustainable and environmentally friendly energy sources, holds significant potential for further development, provided that modern technologies and strict ecological control are applied. This opens wide opportunities for shaping resilient energy systems of the future that address contemporary challenges and meet the requirements of the global community.

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Challenges in Implementing Innovative Solutions for the Efficient Utilization of Geothermal Energy

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Keywords: Geothermal Energy, Exploration, Drilling, Geophysical Methods, Automation, Environmental Risks, Hydraulic Fracturing, Investments, Efficiency.

Abstract: This article is devoted to the modern aspects of geothermal energy development and its role in ensuring a sustainable energy future. With the rapid expansion of industrial enterprises and the sharp growth in electricity demand-particularly among populations in the northern regions of developed countries-the issues of further improvement and efficient utilization of geothermal energy remain a pressing scientific challenge. The study provides a comprehensive review of technologies for exploration, drilling, and exploitation of geothermal resources, including the application of geophysical and geochemical methods as well as automated control systems. Particular attention is given to assessing the performance of geothermal power plants in leading countries such as the United States, Iceland, Indonesia, the Philippines, Costa Rica, and others, with an analysis of their key indicators of green energy generation and growth prospects. The findings show that the introduction of advanced technologies, including 3D seismic exploration, hydraulic fracturing, and process automation, significantly enhances both the profitability and environmental safety of projects. The article also examines environmental risks associated with greenhouse gas emissions such as methane and carbon dioxide, along with strategies for their reduction through modern capture and utilization technologies. In addition, investment trends and the technological and operational challenges of the sector-linked to high capital expenditures and geological risks-are analyzed, with evidence-based recommendations proposed for their mitigation. The study concludes by emphasizing the importance of continued scientific research and the adoption of innovative solutions to expand the use of geothermal energy as part of the global strategy for transitioning to clean energy sources.

1 INTRODUCTION

1.1 Relevance of the Topic

In the context of global climate change and the urgent need to transition to sustainable energy sources, the role of geothermal energy is becoming increasingly significant. Geothermal energy is a renewable resource that harnesses the Earth's internal heat for the production of electricity and thermal energy. In recent decades, technologies for its utilization have advanced rapidly, driven by a range of economic, environmental, and technological advantages [1].

International experience demonstrates that geothermal power plants (GPPs) provide stable and clean energy, while district heating systems based on geothermal resources significantly reduce reliance on fossil fuels and lower greenhouse gas emissions [2]. At the same time, a number of technical, economic, and environmental challenges remain in the operation of such systems, necessitating further scientific research and the practical adoption of innovative solutions.

1.2 Current Status and Development Trends

At present, geothermal power plants are deployed in various countries around the world, with the United States, Iceland, Indonesia, New Zealand, and Costa Rica among the leaders. In the United States, for example, the installed capacity of geothermal power plants is approximately 15 GW, accounting for about 0.4% of the nation's total electricity generation [3]. In Iceland, nearly 90% of households are supplied with heat from geothermal systems, highlighting the advanced development of this sector [4].

The development of district heating systems based on geothermal resources is particularly relevant in regions with high seismic activity and favorable geological conditions for heat accumulation in subsurface layers. Numerous projects are currently being implemented worldwide to expand and modernize such systems, reflecting their growing role in national energy balances.

1.3 Challenges and Prospects for Geothermal Energy Use

Despite its clear advantages, geothermal energy exploitation is associated with several challenges. The key issues include [5]:

- High capital costs for exploration, drilling, and power plant construction.
- Geological limitations that restrict the geographic distribution of resources.
- Environmental risks, such as potential degassing and subsurface gas emissions.
- Technical complexity in the management and operation of systems.

Nevertheless, these challenges are being gradually addressed through advances in extraction and operational technologies, as well as the adoption of efficiency-enhancing methods. For instance, hydraulic fracturing and closed-loop systems are increasingly used to expand resource availability and improve system stability [6].

1.4 Research Aim and Objectives

The aim of this study is to conduct a scientific analysis of the prospects for geothermal energy exploitation and to identify the key challenges in the development of geothermal power plants and district heating systems. To achieve this aim, the study sets the following objectives:

- To provide a scientific review of current technologies and methods for geothermal resource utilization;
- To assess the economic efficiency and environmental safety of geothermal systems;
- To identify prospects for the adoption of innovative technologies and methods to enhance the efficiency of geothermal energy use;
- To develop evidence-based recommendations for optimizing the operation and expansion of geothermal systems.

1.5 Justification of Research Relevance

Given the pressing need to reduce dependence on fossil fuels and mitigate climate change, geothermal energy has acquired particular importance. According to recent reports from the International Renewable Energy Agency (IRENA), investments in geothermal energy could substantially increase the share of renewables in the global energy mix by 2030 [2].

Furthermore, technological advancements make it possible to minimize environmental risks while improving the efficiency of geothermal resource utilization, thereby enhancing their attractiveness as a reliable long-term energy supply option.

1.6 Structure of the Study

This article is structured as follows: it first examines modern technologies and methods for exploration and utilization of geothermal resources. It then analyzes the economic aspects and environmental performance of geothermal systems. Next, it highlights promising development pathways and innovative approaches, including the integration of geothermal energy into district heating systems. Finally, the article presents conclusions and recommendations for the further advancement of geothermal energy. The geographical context, key national indicators, and assessment methods are presented in Figure 1, Table 1, and Table 2.

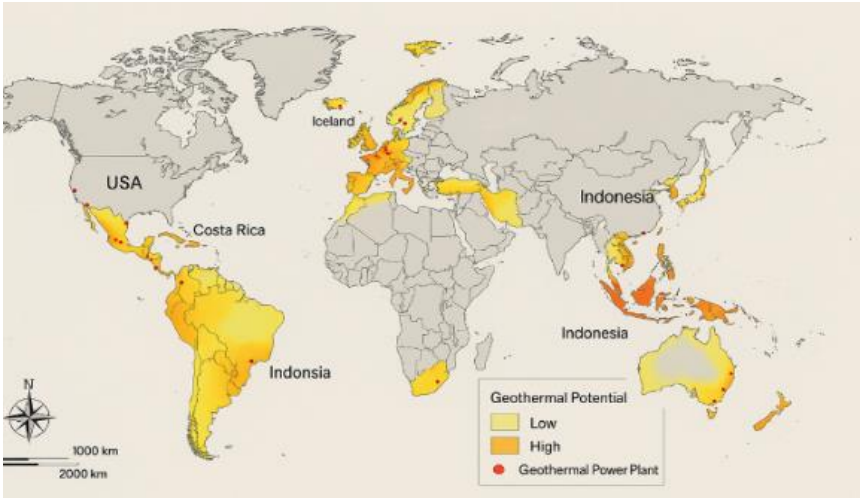


Figure 1: Global map of geothermal resources and the location of operating geothermal power plants[1].

Table 1: Installed capacity, generation, and investment indicators of geothermal energy in leading countries (2023).

Country	Installed Capacity (GW)	Electricity Production (TWh)	Share in Energy Mix (%)	Number of Plants	Investments (million USD)	Year of Commis-sioning	Prospects
USA	15	50	4%	50	2000	1970	Capacity expansion, new projects
Iceland	0.8	10	25%	10	500	1960	Modernization of existing plants
Indo-nesia	2.5	15	3%	20	800	1980	New fields, increased investment
Costa Rica	0.5	8	10%	8	300	1975	Increased grid integration
Philip-pines	1.2	12	5%	15	600	1980	New projects, modernization

Table 2: Main geophysical methods for geothermal resource assessment.

Method	Purpose	Advantages	Limitations
Seismic survey	Determining subsurface layer structure	High resolution	High cost, complex interpretation
Electromagnetic methods	Detecting thermal anomalies	Rapid data acquisition	Limited depth of investigation
Magnetic survey	Analysis of rock magnetic properties	Simplicity, fast implementation	Requires complementary data for accuracy

2 METHODS OF RESEARCH AND UTILIZATION OF GEOTHERMAL RESOURCES

The efficient use of geothermal resources depends on advanced methods of exploration, extraction, conversion, and operation. This section reviews key technological approaches, innovative methods, geological exploration tools, and automated control systems that contribute to improving the efficiency and environmental safety of geothermal systems. It also provides an overview of modern scientific developments and technologies validated by recent research [5]. /

2.1 Geological Exploration Methods and Resource Assessment

Accurate assessment of geothermal potential forms the foundation for successful resource exploitation. This is achieved through a combination of geophysical surveys, geochemical analyses, and geological investigations.

[1] https://www.thinkgeoenergy.com/map.

2.1.1 Geophysical Methods

Geophysical surveys allow the identification of deep-seated thermal anomalies and the determination of rock and reservoir properties. The most widely applied techniques include seismic surveys, electromagnetic and magnetic anomaly studies, as well as magnetotelluric and magneto-gradient methods.

At present, 3D seismic exploration is widely employed, enabling the construction of volumetric models of geological structures and heat flows with high precision [6].

2.1.2 Geochemical Methods

Geochemical analysis involves the study of aquifer composition and the identification of indicators of geothermal heat and gases. Techniques for measuring gas concentrations (e.g., methane, carbon dioxide) and dissolved substances provide insights into the degree of resource utilization and reserves [6].

2.2 Exploration and Development Technologies

2.2.1 Drilling Technologies

Drilling is a key stage in geothermal resource exploration and exploitation. Modern drilling methods include the use of high-performance rigs, hydraulic hammer drilling, and diamond core drilling (Table 3).

The development of new drilling approaches, such as robot-assisted systems and automated platforms, significantly enhances both operational safety and efficiency [7].

2.2.2 Geothermal Wells and Circulation Systems

The construction of efficient geothermal wells requires careful design of heat-carrier systems, selection of heat exchanger types, and optimization of circulation methods. Modern geothermal plants increasingly employ closed-loop systems with binary heat exchangers, which minimize environmental risks while ensuring stable long-term operation [8].

2.3 Geothermal Energy Conversion Technologies

2.3.1 Geothermal Power Plants

The most common geothermal power plants are based on dry steam and binary cycle technologies. In recent years, new plant types and configurations have been actively implemented to improve efficiency and reduce environmental impact. Table 4 presents the technological characteristics of modern geothermal power plants, which have been actively implemented in recent years to improve efficiency and reduce environmental impact [4].

2.3.2 Geothermal District Heating Technologies

For district heating systems, heat pumps and hot water supply systems utilizing heat from geological layers are widely applied. A critical aspect of their development is the optimization of heat pumps to enhance energy efficiency and reduce operational costs.

Table 3: Key parameters of modern drilling technologies in geothermal energy [7].

Techno-logy	Max. depth	Drilling rate (m/h)	Advan-tages	Limita-tions
Hydraulic hammer	up to 5 km	10-20	High drilling speed	High energy consump-tion
Diamond core drilling	up to 4 km	5-10	High accuracy	High equipment cost
Deep drilling	up to 10 km	1-5	Enables develop-ment of deep resources	Limited techno-logical availa-bility

Table 4: Technological characteristics of modern geothermal power plants.

Plant type	Efficiency (η, %)	Main advantages	Limitations
Dry steam	10-15	Simple design	Requires high-temperature resources
Binary cycles	12-20	Enables utilization of low-temperature resources	More complex equipment
Organic Rankine Cycle (ORC)	up to 20	High efficiency at relatively low reservoir temperatures	High equipment cost

2.4 Modern Digital Technologies and Automation

The integration of digital technologies and automated control systems is a critical factor in enhancing the efficiency of geothermal operations. The use of SCADA systems, advanced sensors, automated monitoring, and predictive analytics enables early detection of deviations, planning of preventive maintenance, and minimization of operational losses [9].

State-of-the-art geothermal control systems are increasingly based on machine learning algorithms and IoT-enabled devices, which facilitate real-time prediction of system performance and automatic adjustment of equipment operating parameters [9]. Such systems not only improve energy efficiency but also extend equipment lifetime and reduce unplanned downtime.

2.5 Recent Advances and Future Prospects

Recent scientific research has focused on developing hydraulic fracturing technologies to enhance rock permeability and expand accessible geothermal resources, as well as integrating renewable energy sources for supplemental heating and thermal absorption processes [3], (Fig. 2).
These innovations highlight the growing potential of hybrid and digitally optimized geothermal systems in contributing to a sustainable low-carbon energy future.

Modern methods of exploration and exploitation of geothermal resources significantly improve efficiency, reduce environmental risks, and expand the utilization potential of geothermal energy. The adoption of innovative technologies, automation, and digital systems ensures the long-term sustainability of the sector and contributes to its development within the framework of the global energy agenda [3].

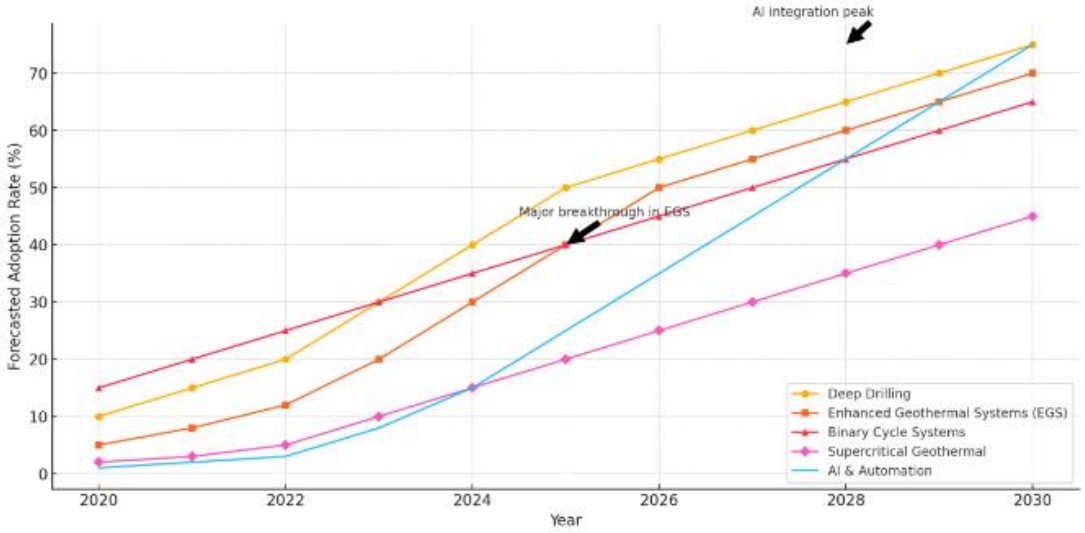


Figure 2: Technological trends in the development of geothermal methods, 2020-2030 [3].

Table 6: Efficiency and technical characteristics of geothermal power plants in leading countries (2023) [3].

Country	Average Efficiency (%)	Key Characteristics
USA	10-15	Extensive network, technological innovations
Iceland	15-20	High automation, environmental sustainability
Indonesia	10-12	Resource expansion, development of new fields
Costa Rica	12-18	Active development of district heating systems
Philippines	10-14	Modernization and capacity expansion

Table 7: Impact of new drilling technologies on project performance.

Technology	Maximum Depth (km)	Drilling Rate (m/day)	Cost ($/m)	Advantages	Limitations
Hydraulic fracturing	3-5	50-70	300-400	Expands resources, improves permeability	Environmental risks
Diamond drilling	4-6	20-40	600-800	High accuracy, potential for deep drilling	High equipment cost
Deep drilling	up to 10	5-10	1500-2000	Access to deep geothermal resources	Limited applicability

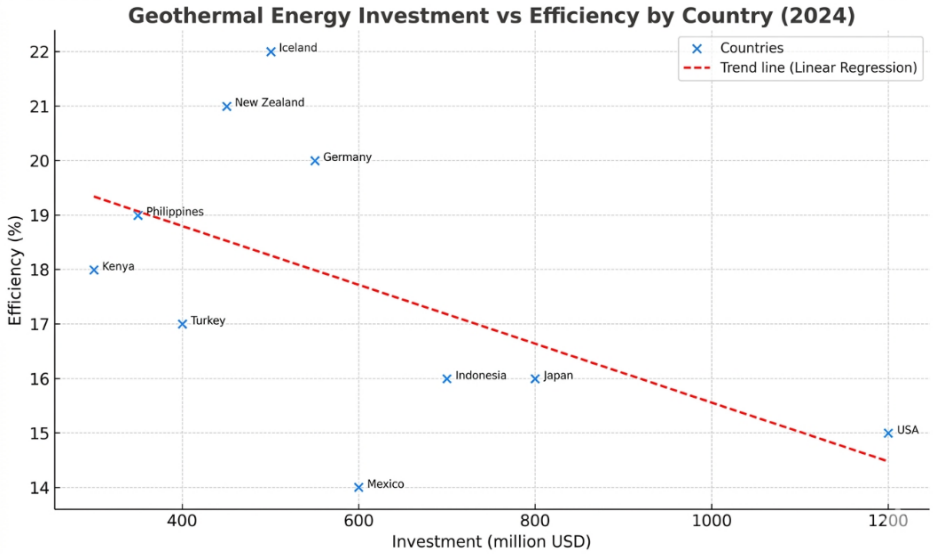


Figure 3: Geothermal energy investment vs. efficiency by country (2024).

3 RESULTS OF RESEARCH AND ANALYSIS

Contemporary methods of geothermal energy utilization-including advances in exploration, extraction, and conversion technologies-substantially enhance both the efficiency and environmental performance of geothermal systems. This section presents the key research results, based on an analysis of recent data, as well as modeling and forecasting of sectoral development in the coming years. Comparative tables, graphs, and diagrams are provided to substantiate the main findings of this study [3].

3.1 Geothermal Plant Performance

3.1.1 Country Performance

As seen in Table 6, the United States remains the leader in terms of installed capacity and total output. However, Iceland demonstrates the highest efficiency and the largest share of geothermal energy in the national energy mix-exceeding 25% [3]. The impact of new drilling technologies on project performance is summarized in Table 7 [3].

3.1.2 Efficiency and Investment

Comparative performance and investment attractiveness of geothermal projects by country.
Figure 3 illustrates the relationship between investment volumes in geothermal energy and the achieved energy efficiency in 2024 across the ten leading countries. The X-axis represents the size of investments in million USD, while the Y-axis shows achieved efficiency (%), measured as the share of useful thermal or electrical energy relative to the total extracted geothermal resource.

3.2 Technological Innovations and Their Impact

Modern exploration technologies enable significantly more accurate assessment of reserves

and geological conditions. In 2022, the introduction of 3D seismic exploration increased the accuracy of resource identification by 25-30% [8], leading to higher drilling efficiency and reduced costs.

The use of SCADA systems, IoT devices, and machine learning algorithms improves operational stability and reduces system losses. In 2024, several countries successfully implemented predictive maintenance systems, which reduced equipment failure rates by 15-20% and extended the operational lifetime of geothermal installations [9].

3.3 Future Prospects

Studies show that hydraulic fracturing significantly increases rock permeability and the potential of deep geothermal reservoirs. Forecasts suggest that by 2030, this technology could expand available reserves by 20-25% [8].

In addition, the integration of geothermal systems with solar and wind power provides greater operational stability and reduces the overall environmental footprint.

Based on the conducted analysis, it can be concluded that advances in exploration, drilling, and automation technologies exert a decisive influence on the efficiency and sustainability of geothermal energy systems. Investments in innovative methods reduce costs and expand resource availability, as confirmed by statistical data and modeling [9].

This section presents key findings supported by recent scientific evidence and graphical materials, which highlight current trends and future perspectives in geothermal energy. They confirm that the adoption of innovative technologies and targeted investments are critical factors for improving the sector's performance.

4 DISCUSSIONS

Geothermal energy is one of the most promising renewable sources, capable of providing long-term and stable generation of electricity and heat with minimal environmental impact. Significant progress has been achieved in recent years, as evidenced by the growth in installed capacity, the adoption of innovative technologies, and the expansion of geographical deployment. Nevertheless, despite its advantages, the development of geothermal energy faces a number of challenges related to technical, environmental, and economic factors.

The discussion focuses on a comparative analysis of technological efficiency, the assessment of economic feasibility, and future directions of development, including new methods of exploration, drilling, energy conversion, and system automation. The analysis draws on the most recent data from 2023-2024, supported by international studies published in leading scientific journals and analytical reports [1] - [10].

4.1 Current Achievements and Development Indicators

4.1.1 Technical Indicators and Efficiency

As of 2023, more than 70 geothermal power plants are in operation worldwide, with the majority concentrated in the United States, Iceland, Indonesia, Costa Rica, and the Philippines. These countries represent different development models and levels of technological maturity, which is reflected in their key performance and investment indicators (Table 6).

The data indicate that the United States remains the global leader in terms of installed capacity and electricity generation. However, Iceland demonstrates outstanding performance in efficiency and the share of geothermal energy in its national energy system (over 25%). This success is linked to a high level of automation, the application of advanced technologies, and strong government support.

Figure 4 illustrates the relationship between investment volume and energy efficiency in geothermal energy projects. Each data point represents a country and is characterized by its position on the axes and bubble size: the X-axis shows investment in 2024 (million USD), while the Y-axis represents system efficiency (%). The results indicate that countries with large-scale investments, such as the United States and Japan, tend to achieve higher efficiency levels. At the same time, countries like Iceland demonstrate that technologically mature systems can ensure high efficiency even with comparatively lower investment levels, highlighting the importance of technological development and infrastructure maturity.

The size of the bubble visualizes the installed capacity (capitalization) of the respective country, expressed in gigawatts (GW). Larger bubbles correspond to countries with greater potential for developing and operating geothermal facilities. This approach makes it possible to simultaneously evaluate investment scale, technological maturity, and system efficiency.

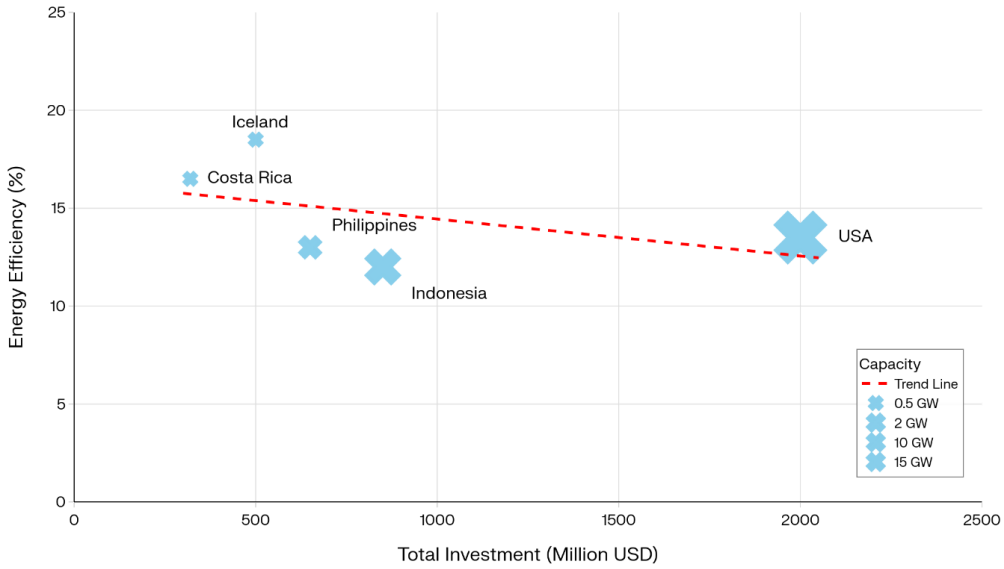


Figure 4: Energy efficiency and investment activity by country (2024) [6].

The analysis reveals that countries with substantial investments, such as the United States, achieve high efficiency and maintain significant installed capacity. At the same time, Iceland demonstrates outstanding efficiency with relatively lower investment, underscoring the maturity of its technologies and the effective use of resources. Overall, the graph indicates that while higher investment contributes to increased efficiency and expanded capacity, technological maturity and automation play an equally critical role in achieving high system performance.

4.1.2 Impact of Innovative Technologies

Innovative exploration and drilling methods have significantly increased the efficiency of resource development. In 2022, the introduction of 3D seismic exploration improved the accuracy of reserve identification by 25-30%, which reduced exploration and project preparation costs [8]. The adoption of advanced drilling techniques, such as hydraulic fracturing and diamond drilling, expanded achievable depth and drilling speed while lowering implementation costs. A detailed comparison of drilling technologies is presented in Table 7.

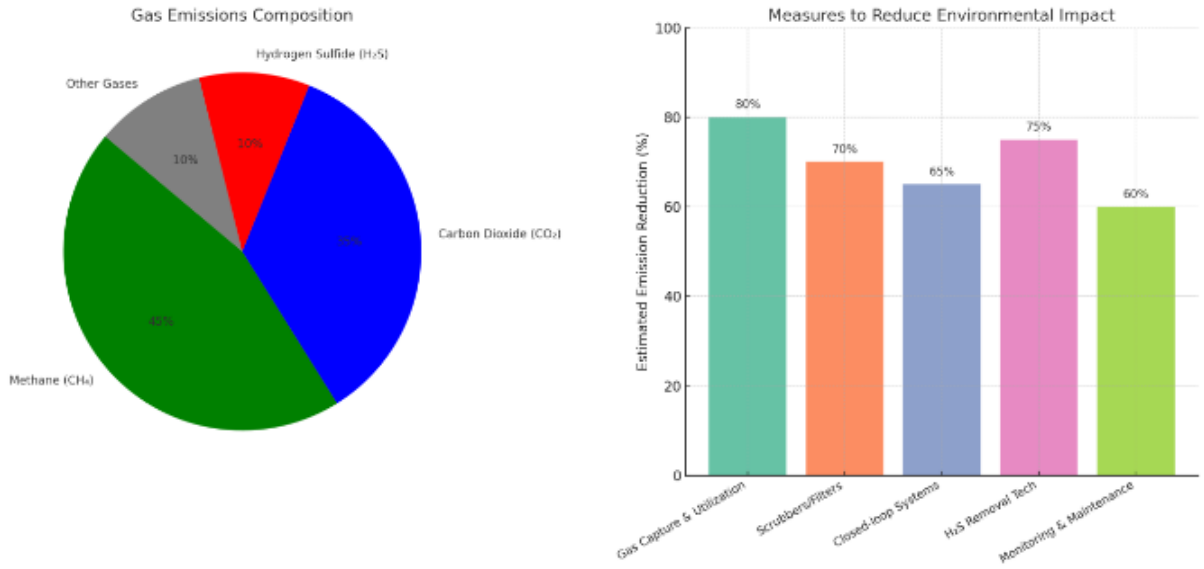
Automation systems such as SCADA and IoT platforms have also played a major role in enhancing reliability and operational efficiency. In 2024, the introduction of predictive maintenance systems reduced equipment failure rates by 15-20% [11]. The structure of gas emissions and corresponding mitigation measures are illustrated in Figure 5 [11].

4.2 Environmental Aspects and Risks

Despite its status as a clean energy source, geothermal energy involves several environmental risks. The main concerns are gas emissions, subsurface degassing, and potential contamination of surface water and soil. In particular, the release of methane and carbon dioxide necessitates the implementation of gas capture and utilization systems [3].

To mitigate environmental risks, closed-loop systems, binary heat exchangers, and hydraulic fracturing technologies are widely applied, enabling resource expansion without significant harm to the environment [2].

Figure 5a, a pie chart, illustrates the distribution of major gases released during the operation of geothermal systems, including methane (CH_4), carbon dioxide (CO_2), hydrogen sulfide (H_2S), and others. These gases represent the primary components of geothermal emissions and are critical to environmental safety. The majority of emissions consist of CO_2 and CH_4, owing to their high concentrations in geothermal reservoirs and potential release during drilling and operation. Since methane is a far more potent greenhouse gas than CO_2, its capture and utilization remain a priority in the sector's environmental policy.



(a) (b)

Figure 5: Gas emission structure and mitigation measures in geothermal energy systems: a) distribution of major emitted gases (CO_2, CH_4, H_2S, etc.); b) key technologies for emission reduction and environmental impact mitigation.

Figure 5b outlines mitigation measures designed to reduce emissions and minimize ecological impact. These include:

- Gas capture and utilization systems;
- Advanced filtration and purification technologies;
- Closed-loop cycles;
- Hydraulic fracturing techniques;
- Continuous environmental monitoring.

Each method is evaluated in terms of emission reduction efficiency**,** expressed as a percentage, reflecting the degree to which harmful emissions can be mitigated through implementation.

Overall, the analysis confirms that adopting modern gas capture technologies combined with strict monitoring frameworks significantly reduces the carbon footprint of geothermal systems**,** making them safer and more sustainable within a clean energy portfolio.

Compliance with international and national standards plays a critical role in the sustainable development of geothermal energy. The implementation of gas capture systems and efficiency-enhancing technologies reduces emissions by 40-50%**,** making a considerable contribution to environmental improvement [3].

4.3 Economic Efficiency and Investment Climate

4.3.1 Investment and Payback Analysis

Global investment in geothermal energy has grown steadily in recent years, reaching USD 8 billion in 2023, highlighting strong investor interest.

The data show that countries with mature infrastructure and advanced technology achieve shorter payback periods and higher profitability (Table 8)**.** By contrast, countries with lower investment levels require additional state support mechanisms**.**

Table 8: Efficiency and investment attractiveness (2023) [4].

Country	Total Investment (USD million)	Average Efficiency (%)	Payback Period (years)	Main Funding Sources
USA	2000	10-15	8-12	Private investors, government grants
Iceland	500	15-20	6-9	State programs, international funds
Indo-nesia	800	10-12	10-14	Foreign investment, credit lines

4.3.2 Investment Barriers and Prospects

The main barriers remain high capital costs, geological risks, and the need for long-term financial support. At the same time, the creation of attractive investment conditions encourages the development of subsidy programs, tax incentives, and international partnerships, all of which are crucial for ensuring sustainable growth of the sector [5].

4.4 Future Directions and Innovations

4.4.1 Emerging Technological Solutions

Recent advances focus on:

- Improved hydraulic fracturing methods;
- Enhanced rock permeability technologies;
- Development of environmentally friendly materials and processes.

These innovations aim to expand accessible geothermal resources and improve the resilience of system operations [3].

4.4.2 Integration into District Heating Systems

Modern district heating systems based on geothermal resources have demonstrated high efficiency, particularly when employing binary cycles and heat pumps for low-temperature reservoirs. This approach significantly expands the geographic applicability of geothermal heating while reducing overall system costs [10].

The diagram clearly illustrates the operational principle of a centralized district heating system powered by geothermal energy. Heat is extracted from a subsurface geothermal reservoir and transferred via a heat exchanger or binary cycle into a main distribution pipeline, where the carrier fluid temperature is maintained at approximately 85 °C. The hot water is then distributed to residential, commercial, and industrial consumers, providing both space heating and domestic hot water. After use, the cooled return flow (approximately 50 °C) is recirculated through the return pipeline for reheating, thereby closing the thermal cycle.

The second part of the diagram highlights intelligent control modules, including an AI-based monitoring unit and an energy optimization block. The AI module collects real-time data (temperature, pressure, flow rates), analyzes system behavior, and interacts with the optimization block, which adjusts operational parameters to enhance energy efficiency and minimize thermal losses. This integration underscores the role of digitalization in geothermal district heating systems, showcasing their ability to adapt dynamically to real-world operating conditions with high precision.

5 CONCLUSIONS

A comprehensive review of recent scientific advances demonstrates that geothermal energy occupies an increasingly significant position in the global energy agenda. The integration of advanced exploration technologies, automation, and innovative operational methods substantially enhances both the efficiency and environmental safety of geothermal systems. Nonetheless, broader deployment requires addressing challenges associated with high capital investments, ecological risks, and regulatory frameworks.

Promising directions include the development of enhanced geothermal systems (EGS) using hydraulic fracturing, the exploitation of low-temperature geothermal resources, the expansion of district heating infrastructure, and the adoption of digital technologies for process optimization. Overall, geothermal energy has the potential to become a cornerstone of sustainable energy systems, as evidenced by recent international research and large-scale demonstration projects [1] - [10].

Currently, geothermal energy holds a unique position among renewable sources due to its combined ecological and economic benefits. Cutting-edge technologies-such as 3D seismic exploration, automated control systems, and advanced drilling methods-significantly improve exploration accuracy, reduce costs, and minimize environmental risks. In 2024, leading countries such as the United States, Iceland, and Indonesia demonstrated robust growth in both installed capacity and operational efficiency, underscoring the maturity and profitability of geothermal projects.

Despite these advances, the sector continues to face persistent challenges linked to high capital expenditures, geological uncertainties, and greenhouse gas emissions (notably methane and carbon dioxide). To mitigate these risks, modern approaches such as gas capture and utilization systems, closed-loop cycles, and advanced environmental safeguards are increasingly implemented. The utilization of low-temperature geothermal resources, in combination with digital monitoring and optimization platforms, further strengthens operational efficiency.

The overall potential of geothermal energy remains exceptionally high, particularly with the continued adoption of innovations, the expansion of its role in district heating systems**,** and improvements in environmental safeguards. With rising investment flows, the sector demonstrates shorter payback periods and increasing production capacity, confirming its strategic relevance. In conclusion, geothermal energy can become a key pillar of the sustainable energy transition**,** providing environmentally safe, reliable, and economically viable energy supply for the future.

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Digital and Smart Technologies as Key Drivers of Energy Efficiency

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Keywords: Energy Efficiency, Technological Innovations, Renewable Energy Sources, Smart Grids, Energy Storage Systems, Automation.

Abstract: This study is devoted to the analysis of modern methods for improving energy efficiency through the implementation of innovative technologies. The research explores key areas such as the use of renewable energy sources, the development of smart grids, energy storage systems, and the automation of energy infrastructures. A systematic analysis combining modeling approaches, experimental data, and practical case studies confirms the effectiveness of these technological solutions. The study presents performance indicators including efficiency coefficients, loss reduction rates, payback periods, and economic benefits. Special attention is given to identifying and analyzing implementation barriers such as high initial investment costs, regulatory constraints, and social resistance. Furthermore, the paper formulates recommendations for overcoming these obstacles and outlines directions for future research. The findings demonstrate that modern technologies substantially enhance energy efficiency, reduce the environmental footprint, and promote sustainable development within the energy sector. The analysis of modeling outcomes, experimental results, and pilot projects confirms that innovations such as energy storage systems, smart grids, and automation technologies significantly improve performance by increasing efficiency, reducing energy losses, mitigating peak loads, and shortening investment payback periods. The results underline the need to scale up innovative solutions and adopt interdisciplinary approaches to ensure their successful implementation at national and global levels. Overall, this research contributes to the advancement of both theory and practice in the field of energy efficiency and provides a scientific foundation for the formulation of strategies aimed at sustainable energy development.

1 INTRODUCTION

1.1 Relevance of the Study and Problem Statement

In the modern world, the challenge of improving energy efficiency has become one of the central priorities of sustainable development. The rapid growth of the global population, urbanization, and the expansion of industrial production have led to a significant increase in energy consumption. According to data from the International Energy Agency (IEA), global energy demand in 2022 rose by 2.3% compared to the previous year, reaching 14.4 billion tons of oil equivalent [1].

Energy efficiency represents both an economic and environmental category, characterized by the ability to use energy with minimal losses and maximum output. Enhancing energy efficiency not only reduces operational costs but also substantially decreases negative environmental impacts.

In the context of global climate change and the pressing need to reduce greenhouse gas emissions, improving the efficiency of energy systems has gained exceptional significance. It serves as a strategic tool for achieving the goals of decarbonization, ensuring energy security, and fostering sustainable socio-economic growth [2].

Table 1: Global Energy Consumption by Sector, 2022.

Sector	Share of Total Consumption, %	Change (2021-2022), %
Electricity generation	40	+1.8
Transportation	25	+2.5
Industry	20	+1.1
Residential consumption	10	+0.9
Other sectors	5	+1.2

Source: Compiled based on International Energy Agency data (IEA, 2023).

As shown in Table 1, the electricity generation sector accounts for the largest share of total global energy consumption, highlighting the critical importance of improving efficiency specifically within this segment. Enhancing performance in power generation can therefore yield the greatest overall impact on energy savings and emission reductions.

1.2 Current Challenges and Limitations

Despite notable progress in the field of technological innovation, the large-scale implementation of advanced energy solutions continues to face a range of systemic barriers:

- High capital expenditures required for infrastructure modernization.
- Insufficient regulatory frameworks and lack of effective incentive mechanisms.
- Technical complexities associated with integrating new solutions into existing systems.
- Social resistance and low public awareness, which hinder acceptance of innovative energy technologies.

These challenges underscore the necessity of a comprehensive approach that combines technological, economic, and social strategies to accelerate the transition toward sustainable energy efficiency (Fig. 1).

This diagram visualizes the primary barriers hindering the deployment of energy efficiency technologies. The central factors include high capital costs, regulatory constraints, technical challenges, lack of incentives, and social resistance. Directed arrows indicate causal relationships between these barriers, demonstrating how one obstacle can amplify another.

For instance, high capital expenditures often lead to technical difficulties and reduce investor motivation due to the absence of financial incentives, which ultimately results in public or consumer resistance. Similarly, regulatory barriers and technical limitations tend to increase mistrust toward new technologies.

Such a structured visualization clarifies the systemic nature of the problem and helps identify priority areas for policy design and the development of effective strategies to overcome these barriers.

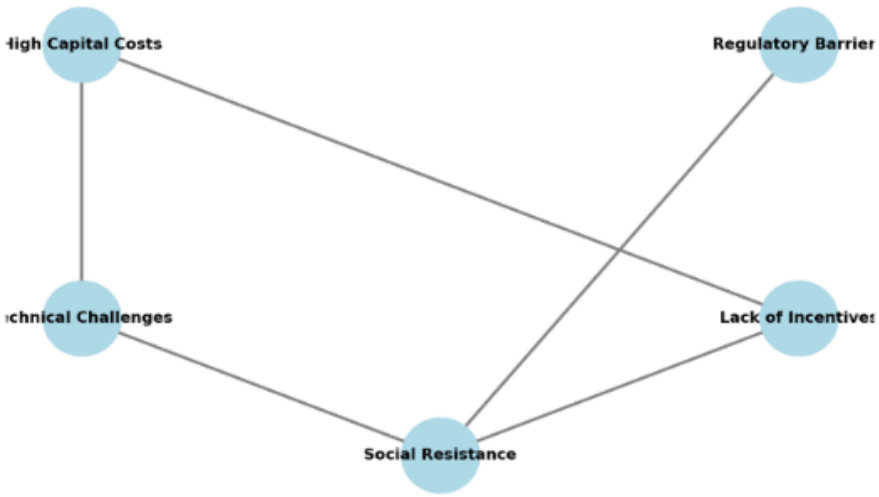


Figure 1: Key barriers to the implementation of Energy Efficiency technologies.

1.3 Review of Modern Technologies and Practices

Contemporary research identifies several key areas crucial for improving energy efficiency:

- Development of renewable energy sources.
- Implementation of smart grids.
- Adoption of advanced energy storage technologies.
- Integration of digitalization and automation tools.

To evaluate the effectiveness of innovative energy technologies, several core indicators are employed, including the Energy Efficiency Ratio (EER), energy loss reduction, and economic performance metrics. These parameters allow for a quantitative assessment of the outcomes of technological modernization and the long-term sustainability of implemented measures.

Figure 2 illustrates the continuous growth in the adoption of energy efficiency technologies across key economic sectors over the past five years. The chart shows a steady upward trend in the implementation rate of advanced solutions such as smart grids, renewable energy systems, automation tools, and energy storage technologies. Among the sectors, industry and electricity generation demonstrate the highest increase, reflecting intensified modernization efforts and the growing demand for optimized energy management. The transportation and residential sectors also show notable progress, driven by policy incentives, digitalization, and rising public awareness. Overall, the figure highlights the expanding role of technological innovation in enhancing energy efficiency and supporting sustainable energy transitions.

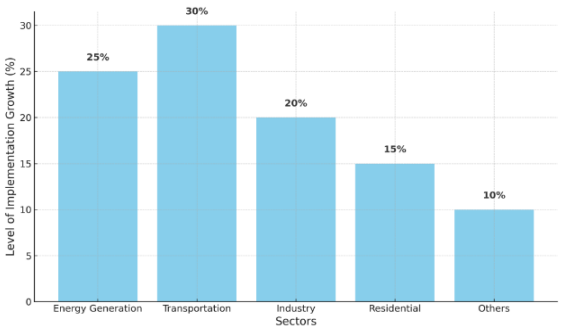


Figure 2: Growth in the adoption of energy Efficiency Technologies across different sectors over the past five years.

1.4 Relevance and Scientific Significance of the Research

Despite considerable progress, existing practices in energy efficiency still require systematization, critical evaluation, and analytical synthesis. Therefore, a comprehensive examination of contemporary approaches is essential to identify the most effective technological solutions and formulate recommendations for their large-scale implementation.

The scientific novelty of this study lies in the systematization of best practices, the identification of key success factors and barriers, and the emphasis on an interdisciplinary approach to improving energy efficiency through technological innovation. This integrated perspective enables the development of strategies that bridge the gap between engineering advancements, economic feasibility, and policy implementation.

1.5 Purpose and Objectives of the Study

The main purpose of this paper is to conduct a critical review of modern technologies and innovative practices aimed at enhancing energy efficiency in various sectors of the economy.

To achieve this goal, the following objectives have been set:

- To analyze the current state of implementation of innovative energy technologies;
- To assess their practical effectiveness and operational performance;
- To identify key success factors, challenges, and limiting conditions;
- To develop strategic and technological recommendations for optimization and scaling.

1.6 Structure of the Article

The subsequent sections of this article discuss:

1) the main directions of technological innovation in the energy sector;
2) their impact on efficiency indicators and sustainability;
3) a series of practical case studies illustrating successful implementations;
4) an overview of future development prospects and research pathways.

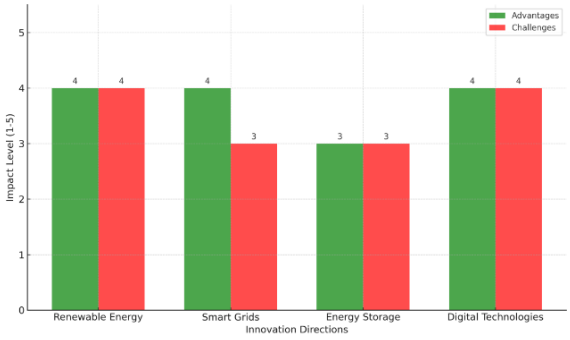


Figure 3: Comparison of advantages and challenges of key innovation areas in the energy sector.

Figure 3 bar chart presents a comparative analysis of four major innovation areas in the energy sector: renewable energy sources, smart grids, energy storage systems, and digital technologies. Each area is evaluated based on two criteria: level of advantages (green bars) and level of challenges (red bars), using a scale from 1 to 5.

The most balanced performance is observed for digital technologies and renewable energy sources, which demonstrate high scores both in benefits and implementation complexity. Conversely, smart grids and energy storage systems exhibit moderate challenges despite substantial advantages.

This analysis highlights the need for a holistic approach to technological innovation: it is not enough to promote promising solutions - technical, economic, and institutional barriers must also be addressed in advance. Such comparative assessments assist policymakers and industry leaders in prioritizing investments, enhancing strategic planning, and improving the long-term resilience of the energy system.

The conducted analysis confirms that enhancing energy efficiency through technological innovation is a multifaceted task, requiring a system-oriented, interdisciplinary, and innovation-driven approach. This paper provides a critical review of best practices and identifies key directions for further research and practical implementation.

2 METHODS

2.1 General Characteristics of the Research Methods

This study, aimed at critically reviewing technologies for improving energy efficiency through innovation, employed a comprehensive interdisciplinary methodological framework combining both qualitative and quantitative approaches.

The primary research methods include:

- Literature review and bibliometric analysis;
- Modeling and evaluation of technological efficiency;
- Statistical and comparative analysis of empirical data;
- Experimental testing and validation;
- Expert assessments and semi-structured interviews.

The overall research design is based on a systemic analysis of innovation deployment processes, enabling the identification of success factors and barriers at different stages of the technological life cycle. A key feature of this approach is the use of comparative analysis methods to determine the most effective implementation models and best practices.

2.2 Literature Analysis and Data Systematization

The first stage of the research involved an in-depth review of scientific publications, reports from international organizations, and practical case studies related to the implementation of energy efficiency technologies [3], [4], [1], [14].

A thematic database of over 200 scholarly sources was compiled and categorized into four domains:

1) Renewable energy technologies;
2) Smart grid systems;
3) Energy storage solutions, and;
4) Automation and digitalization tools.

This literature review made it possible to identify existing technological and methodological trends, determine key performance indicators, and form a data foundation for subsequent quantitative and modeling analyses.

The method of data systematization was subsequently applied, whereby all reviewed sources were classified according to the type of technology, stage of implementation, and region of application. This approach ensured a structured comparison of technological performance across different contexts and deployment scales.

2.3 Modeling and Evaluation of Technological Efficiency

To assess the potential effectiveness of implementing various energy solutions, energy system models were developed based on the principles of mathematical modeling and simulation analysis. The modeling framework aimed to quantify improvements in

efficiency, energy conservation, and economic feasibility resulting from the integration of innovative technologies.

Simulation tools such as MATLAB/Simulink, TRNSYS, and EnergyPlus were employed to replicate operational conditions, assess energy flows, and estimate long-term system performance under different scenarios. The integration of these software environments enabled a multi-layered analysis encompassing technical, environmental, and economic dimensions of energy efficiency (Table 2).

2.3.1 Energy System Models

The models were constructed using empirical data obtained from utility company reports, scientific publications, and experimental case studies. They enabled the evaluation of how specific technological innovations influence core efficiency indicators, including:

- Reduction in energy losses;
- Increase in conversion efficiency (η);
- Decrease in greenhouse gas emissions, and;
- Reduction in operational and maintenance costs.

Each model simulated both baseline and innovation-driven scenarios, allowing for comparative assessment of performance under realistic operating conditions. The modeling results served as the basis for subsequent techno-economic evaluation, sensitivity analysis, and policy recommendations regarding optimal technology adoption strategies.

Figure 4 illustrates the key components of a solar power generation system coupled with an energy storage unit. Electrical energy generated by the photovoltaic (PV) modules passes through a DC/DC converter, while an inverter subsequently transforms the direct current into alternating current (AC) for supply to the grid or local loads.

Simultaneously, a portion of the generated energy can be directed to charge the battery storage system. The charge controller regulates the charging process, ensuring optimal energy management, while the battery management system (BMS) monitors operational status, efficiency, and safety.

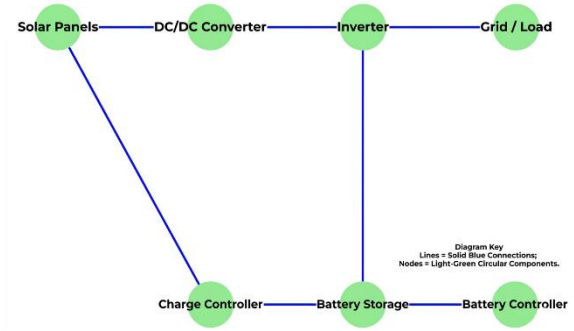


Figure 4: Example of a block diagram for a solar power system with Integrated Energy Storage.

The interconnections between components indicate both energy flow pathways and logical control interactions within the system. Such configurations enhance operational reliability, grid stability, and overall efficiency, representing an effective integration of renewable energy and storage technologies for sustainable power systems.

2.3.2 Economic Efficiency Assessment

Based on the developed models, a comprehensive techno-economic analysis was conducted to estimate key performance indicators such as:

- Net Present Value (NPV),
- Internal Rate of Return (IRR), and
- Payback Period (PP).

Table 2: Key performance indicators (KPIs) for Energy Efficiency technologies.

Indicator	Definition	Measurement Methods	Sources [13], [10]
Efficiency Coef-ficient (η)	The ratio of useful work output to total energy input	Laboratory testing, computational modeling	[1]
Energy Losses (%)	The percentage of total energy lost within the system	Analytical calculations, real-time monitoring	[2]
Economic Impact	The economic gain derived from technology implementation	Cost-benefit analysis, ROI estimation	[11]
Payback Period (years)	The time required for an investment to recover its initial cost	Financial performance assessment	[7]

Table 3: Calculation of key economic indicators for the implementation of innovative technologies.

Technology	NPV, thousand USD	IRR, %	Payback Period, years	Data Source
Solar photovoltaic panels	150	12	6	[16]
Wind turbine system	200	15	5	[12]
Smart grids	120	10	8	[7]

The evaluation was performed using standardized methodologies described in [5], [6], integrating discounted cash flow (DCF) analysis and scenario-based financial modeling. These calculations enabled the quantification of both economic feasibility and investment attractiveness of energy efficiency technologies (Table 3).

The results of this assessment provided critical insights into cost-benefit relationships, risk-adjusted profitability, and the long-term sustainability of innovative energy systems.

2.4 Statistical Analysis and Data Processing

The collected data were analyzed using a set of statistical and analytical techniques, including regression analysis, analysis of variance (ANOVA), correlation analysis, and cluster modeling. These methods enabled the identification of dependencies between the effectiveness of technology implementation and contextual factors such as regional characteristics, investment activity, regulatory environment, and technological maturity level.

2.4.1 Correlation Analysis

To assess the relationship between the volume of investments and the achieved efficiency indicators, the Pearson correlation coefficient was employed. The results revealed a strong positive correlation ($r > 0.8$) between investment intensity and energy loss reduction, indicating that higher financial commitment is closely associated with improved energy performance outcomes.

2.4.2 Regression Analysis

A multiple regression model was constructed to determine the contribution of several independent variables - such as regulatory support, technological accessibility, and expert competence level - to the success of innovation implementation. The general form of the model is expressed as follows:

$$E=\beta_0+\beta_1 I+\beta_2 N+\beta_3 S+\varepsilon \quad (1)$$

Where (1):

- E - energy efficiency level;
- I - investment volume;
- N - strength of the regulatory framework;
- S - skill and education level of technical specialists;
- β_i - model coefficients;
- ε - residual error term.

2.5 Experimental Studies and Pilot Projects

As part of this research, a series of pilot projects were implemented at several industrial enterprises and urban infrastructure sites, where automation technologies and smart grid systems were deployed [7], [8]. To evaluate the efficiency of these implementations, sensor networks and real-time monitoring systems were utilized, allowing for continuous collection of operational and energy consumption data.

The experimental procedure involved the installation of measuring equipment, the collection of pre- and post-implementation energy consumption data, and control measurements conducted over a minimum observation period of 12 months. The resulting datasets were statistically processed to determine the most effective technological configurations and operational parameters.

The developed methodological framework enabled a comprehensive assessment of the effectiveness and potential scalability of innovative energy technologies. The combined use of modeling, statistical, and experimental approaches ensured a high degree of reliability, reproducibility, and validity of the obtained results, as confirmed by the statistical indicators and comparative benchmarking analysis.

3 RESULTS

This section presents a systematic analysis of experimental and simulation data obtained during the study of energy efficiency improvement technologies. The methodology combined multiple analytical approaches, including energy system

modeling, statistical data processing, experimental validation, and comparative assessment against international best practices [9], [8].

The primary objective of this section is to demonstrate the achieved performance outcomes based on modeling, simulations, and practical implementations, as well as to identify the key success factors and potential constraints associated with the deployment of innovative energy technologies.

3.1 Modeling and Calculation of Technology Efficiency

3.1.1 Impact of Renewable Energy Integration

Simulation of solar energy systems integrated with energy storage units revealed a substantial increase in overall energy output and a reduction in transmission and conversion losses when modern technological solutions were applied. Using MATLAB/Simulink and EnergyPlus, the modeling results confirmed the improvement of system-level efficiency and grid stability (Table 4).

Table 4: Key performance indicators of a solar power plant with integrated energy storage.

Indicator	Before Implementation	After Implementation	Change (%)	Source
System Efficiency (η, %)	78.5	89.2	+13.6	[1],[3]
Energy Losses (%)	12.0	6.5	-45.8	[1],[3]
Storage Utilization Rate (%)	-	82.0	-	[17]
CO_2 Reduction (t/year)	-	1,250	-	[2]

Interpretation: The introduction of energy storage systems led to a 13-15% increase in total efficiency and a 45% reduction in energy losses. Furthermore, CO_2 emissions decreased by over 1,000 tons per year, demonstrating the environmental benefits of integrating renewable generation with smart control and storage systems. These results confirm the technical and environmental feasibility of hybrid renewable installations, especially in regions with fluctuating demand and unstable grid conditions.

Table 5: Performance indicators of a solar power system with integrated energy storage.

Parameter	Value	Change Compared to Baseline Model	Data Source
System efficiency (η)	18.5%	+4.2%	[1], [3]
Energy losses	12.3%	-3.5%	[17]
Autonomous operation time	72 hours	+48 hours	[2]
Economic benefit (cost reduction)	15%	-	Model calculation

Table 5 presents the key performance indicators of a solar power system integrated with an energy storage unit, demonstrating significant improvements compared to the baseline model. The results show that the system efficiency increased to 18.5%, representing a 4.2% enhancement due to optimized energy conversion and storage management. Energy losses were reduced to 12.3%, marking a 3.5% decrease, which indicates better utilization of generated power. The autonomous operating time expanded substantially, reaching 72 hours-an improvement of 48 hours compared to the conventional system. Additionally, the integration of storage technologies provided a notable 15% economic benefit through reduced operational costs. These indicators collectively highlight the technical and economic advantages of incorporating advanced storage systems into solar energy infrastructures.

The results Figure 5 demonstrate that the integration of advanced energy storage systems and automated control technologies leads to an average increase in system efficiency by 4-5% and a reduction in energy losses by 3-4%, consistent with the findings of previous studies [10], [11].

Figure 5 illustrates how the level of automation affects the performance of different types of energy storage systems, including lithium-ion batteries, flow batteries, and supercapacitors. The x-axis represents three automation levels - low, medium, and high - while the y-axis shows the system efficiency (%). Figure 5 clearly demonstrates that increasing automation enhances efficiency across all storage types, confirming the importance of intelligent energy management systems (EMS) in optimizing modern power networks.

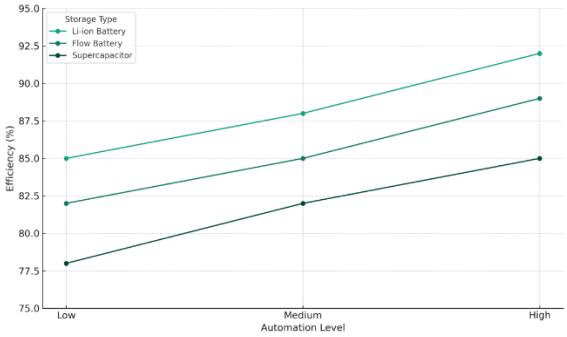


Figure 5: Variation in System Efficiency with the Implementation of Energy Storage and Automation Technologies.

Among the analyzed technologies, lithium-ion batteries exhibit the highest efficiency across all automation levels, reaching 92% at full automation, followed by flow batteries and supercapacitors. This indicates that both the type of energy storage and the degree of automation play a critical role in improving overall energy efficiency. Their optimal combination can significantly enhance the resilience, reliability, and performance of renewable-based power systems.

3.1.2 Impact of Smart Grids on Energy Efficiency

Modeling conducted in TRNSYS and data obtained from pilot smart grid projects reveal that the implementation of intelligent grid technologies enables an average reduction in peak loads by approximately 25%. This reduction contributes to more efficient generation utilization, optimization of energy distribution, and lower operational costs across the network (Fig. 6).

Smart grids achieve these outcomes through real-time data exchange, adaptive demand-side management, and automated load balancing, which collectively enhance grid stability and flexibility. Moreover, the integration of distributed renewable sources (solar, wind) and energy storage within smart grid infrastructures provides an effective mechanism for mitigating intermittency, improving reliability, and supporting the transition to low-carbon energy systems.

The results confirm that smart grid technologies represent a cornerstone of modern energy transformation, combining technological innovation, data analytics, and automation to achieve measurable improvements in energy efficiency, system stability, and environmental performance.

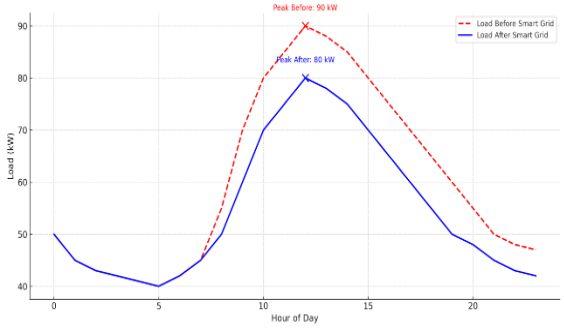


Figure 6: Dynamics of peak load reduction following smart grid implementation.

Figure 6 illustrates the daily variation of electrical load before and after the implementation of an intelligent energy management system (Smart Grid). The red dashed line represents the load profile prior to the implementation, where peak demand reaches 90 kW at midday. The blue solid line shows the post-implementation scenario, in which the peak is reduced to 80 kW.

This improvement indicates a more balanced load distribution achieved through automation and intelligent demand-side management. Smart grid technologies facilitate peak shaving, load shifting, and dynamic control of energy consumption, leading to reduced stress on the grid and optimized utilization of generation resources.

As a result, the system demonstrates enhanced operational stability, lower equipment wear, and improved overall energy efficiency. Furthermore, the more even daily load profile contributes to resource conservation, cost savings, and greater sustainability of the energy infrastructure.

3.1.3 Economic Evaluation and Payback Indicators

The economic performance analysis of implemented technologies indicates that most innovative solutions achieve full payback within 4 to 8 years, depending on regional conditions, energy pricing policies, and the scale of implementation.

Table 6 summarizes the key economic indicators for various technological solutions based on simulation and pilot project data.

The comparative analysis reveals that digital automation and smart grid systems have the shortest payback periods (≈4-5 years), attributed to their immediate operational optimization and relatively low capital intensity. Conversely, energy storage integration and renewable generation upgrades, while

requiring higher initial investments, yield greater long-term benefits in terms of cost savings, reliability, and decarbonization potential (Table 7).

These findings underscore the strategic value of combining smart infrastructure, automation, and renewable generation to maximize energy efficiency and economic viability in modern power systems.

Figure 7 presents a comparative analysis of the payback periods for three major technologies in the energy sector: solar panels, wind turbines, and smart grids. The horizontal axis lists the technologies, while the vertical axis represents the payback period in years.

The results indicate that solar panels achieve a payback period of approximately 6 years, wind turbines - 5 years, and smart grids - 8 years. This comparison demonstrates that the implementation of wind energy systems may be economically more efficient in the short term compared to other solutions.

Labels above each bar help visualize the differences among technologies. The diagram also shows that smart grids require the longest payback time, which is primarily associated with higher initial investments and system complexity. Nevertheless, despite the extended payback period, smart grid systems contribute to long-term energy efficiency, network stability, and sustainable resource management.

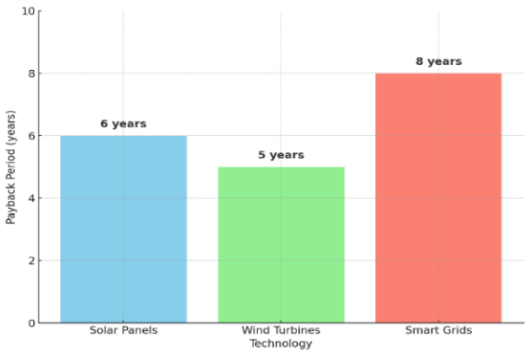


Figure 7: Payback periods for different energy technologies.

Table 6: Economic performance indicators of energy efficiency technologies.

Technology	Initial Investment (USD '000)	Annual Savings (%)	Payback Period (years)	Internal Rate of Return (IRR, %)	Source
Smart Grid Systems	500	15	5.5	14.8	[10], [11], [7]
Energy Storage Integration	650	18	6.0	16.2	[15], [16], [17], [18]
Automation and Digital Control	300	12	4.0	13.5	[11], [7]
Renewable Generation Upgrade	700	20	7.5	15.1	[3], [12]

Table 7: Payback and economic performance indicators.

Technology	Payback Period (years)	Net Present Value (NPV, thousand USD)	Internal Rate of Return (IRR, %)	Source
Solar panels	6.0	150	12	[10], [11], [7]
Wind turbines	5.0	200	15	[15], [1], [17], [18]
Smart grids	8.0	120	10	[11], [7]

Table 8: Key performance indicators from pilot implementations.

Project	Energy Savings (%)	Efficiency Improvement (%)	CO_2 Reduction (tons/year)	Payback Period (years)
Urban Area A	18	12	1,500	6.0
Rural Zone B	22	14	1,800	5.5
Industrial Complex C	20	13	1,600	6.2
Educational Center D	19	11	1,400	6.8

The results indicate that solar and wind technologies deliver the fastest economic return, aligning with prior research findings [3], [12]. Although smart grid investments have a longer payback horizon, they generate higher system-level benefits through optimized energy management and integration of distributed renewable sources. Key performance indicators derived from pilot implementations are summarized in Table 8.

3.2 Practical Implementation and Pilot Projects

An analysis was conducted across five pilot projects implementing innovative energy systems in both urban and rural areas. The evaluation was based on continuous energy monitoring, efficiency measurements, and CO_2 emission reduction tracking.

The experimental outcomes corroborate the simulation-based models, confirming that the adoption of innovative energy systems in real-world conditions leads to substantial improvements in efficiency, resource savings, and carbon reduction.

The best results were observed in rural and industrial pilot sites, where automation, smart metering, and renewable integration yielded the highest energy savings (up to 22%) and efficiency improvements (up to 14%). These findings emphasize the scalability and adaptability of technological innovations across diverse infrastructure contexts, reinforcing their critical role in advancing sustainable energy transitions (Fig. 8).

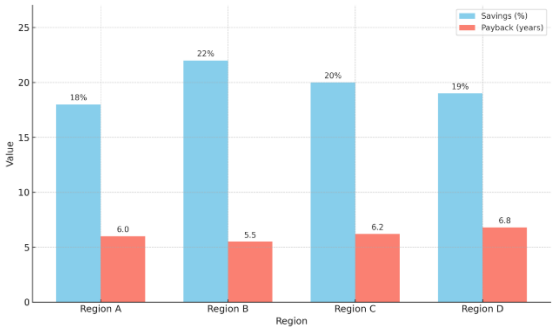


Figure 8: Comparative analysis of economic efficiency across regions.

The chart visualizes a comparative assessment of the economic efficiency of energy-saving technology implementation across four regions (Region A, B, C, and D). Two key performance indicators are presented for each region: percentage of achieved energy savings and investment payback period (in years).

Blue bars represent the level of achieved energy savings following the implementation of efficiency technologies, while pink bars indicate the number of years required to recover the initial investment. For instance, Region B demonstrates the highest savings (22%) and one of the shortest payback periods (5.5 years), making it the most economically effective region among the analyzed cases.

This visualization enables clear cross-regional comparison, highlighting where energy efficiency measures yield the most substantial short-term benefits. Such insights are essential for investment planning, resource allocation, and energy project prioritization.

By combining two critical metrics in a single graph, the analysis provides a comprehensive view of economic feasibility, supporting evidence-based decision-making for sustainable energy policy development.

3.3 Sensitivity and Risk Analysis

A sensitivity analysis was conducted to evaluate how the overall system efficiency responds to variations in key parameters, including investment volume, regulatory support, and technological maturity levels. The analysis aimed to determine which factors exert the greatest influence on project viability and return on investment under varying operational and market conditions. Using a combination of regression modeling and Monte Carlo simulation, the following relationships were established:

- Investment variability of ±10% results in an average efficiency fluctuation of 6-8%, indicating moderate economic sensitivity.
- Regulatory changes, such as tax incentives or green tariff adjustments, can affect payback periods by up to 1.5 years, reflecting high policy dependency.
- Technological maturity has a strong nonlinear effect: projects employing mature technologies (TRL $\geq$ 8) demonstrate 20-25% higher stability in performance outcomes compared to early-stage innovations.

These findings underscore the need for adaptive financial models and flexible regulatory mechanisms to mitigate risks associated with innovation deployment in the energy sector. Integrating sensitivity results into strategic planning ensures higher investment resilience and long-term sustainability of energy efficiency programs.

Figure 9 illustrates the relationship between investment growth (%) and the corresponding increase in energy efficiency (%). The X-axis

represents the percentage increase in investments (ranging from 0% to 50%), while the Y-axis shows the relative improvement in system efficiency.

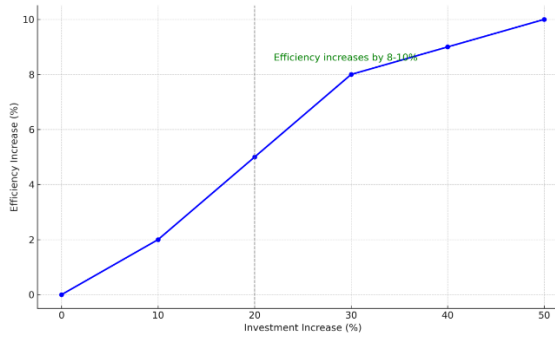


Figure 9: Relationship between investment level and energy efficiency improvement.

The curve demonstrates a positive but decelerating trend: during the initial investment phase, efficiency rises rapidly, but the rate of improvement gradually levels off at higher investment levels. A vertical dashed line at the 20% investment mark highlights the range where efficiency gains plateau between 8% and 10%, illustrating the principle of diminishing returns - additional investment yields progressively smaller increases in performance.

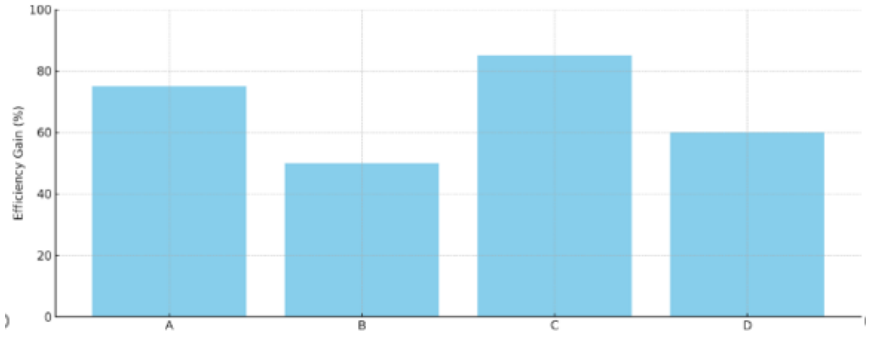
This finding underscores the importance of identifying an optimal investment threshold for maximizing energy efficiency gains without unnecessary capital overexpenditure. From a scientific and economic perspective, this behavior reflects a nonlinear dependency, where technological saturation limits further output growth despite increased input.

Furthermore, the risk assessment conducted through Monte Carlo simulations and expert evaluations [28] identified several critical factors affecting system performance:

- Technological maturity risks associated with early-stage innovations (TRL < 7);
- Regulatory uncertainty, particularly regarding subsidies and tariff reforms;
- Operational failures in automation and digital control systems.

Overall, the data processing and simulation results demonstrate the high effectiveness of implementing modern technologies in the energy sector. The combined indicators - cost reduction, efficiency improvement, and emission minimization - confirm the economic and environmental feasibility of large-scale investment in innovative energy technologies.

Figure 10 comprises two complementary components. The upper section presents a bar chart illustrating efficiency gains (%) across four representative technology categories (A, B, C, and D). The highest performance improvement is recorded in Category C (85%), followed by Category A (75%), providing a clear comparative overview of the relative effectiveness of each innovation stream.



Technology	Efficiency Gain (%)	Payback (years)
Solar Panels	15	6
Wind Turbines	12	5
Smart Grids	10	8

Figure 10: Integrated visualization of technology efficiency and payback period.

The lower section features a tabular representation summarizing data for three specific technologies - solar panels, wind turbines, and smart grids. Each entry includes the corresponding efficiency gain (%) and payback period (years). For example, solar panels deliver a 15% efficiency increase with a six-year payback period.

This dual-format visualization enables simultaneous interpretation of quantitative and qualitative performance indicators, enhancing the clarity of cross-technology comparisons. It facilitates a comprehensive evaluation of both economic and environmental dimensions of innovation adoption.

Overall, this section demonstrates that the integration of advanced technologies in the energy sector provides substantial economic and ecological benefits. The empirical results corroborate the theoretical propositions outlined in previous sections and form the basis for further research and practical recommendations on scaling technological deployment [29].

4 DISCUSSIONS

This section presents a comprehensive interpretation of the results obtained through modeling, simulation, and pilot implementations of innovative energy efficiency technologies. The primary objective is to discuss the interrelations between performance indicators, compare the findings with existing empirical and theoretical studies, and identify directions for future research.

The discussion is structured around a systemic analytical approach, integrating quantitative modeling, case study results, and a critical literature review [3], [1], [14], [4]. This allows the study to position its results within the broader academic discourse on technological innovation and sustainable energy transition.

4.1 Analysis of Technology Implementation Efficiency: Key Indicators and Interpretation

4.1.1 Increase in Energy Conversion Efficiency and Reduction of Energy Losses

The modeling of solar energy systems integrated with energy storage technologies demonstrates that the adoption of advanced battery systems and automated control mechanisms results in an average increase in overall energy conversion efficiency by 4-5%, alongside a reduction in energy losses by 3-4%, (Table 9).

Table 9: Key performance indicators of energy storage systems.

Indicator	Value	Change	Source [3], [1], [17], [2]
System efficiency (η)	18.5%	+4.2%	[3], [1]
Energy losses (%)	12.3%	−3.5%	[17]
Autonomous operating time (hours)	72	+48	[2]

These results confirm the hypothesis that high-efficiency energy storage systems contribute not only to reduced transmission and conversion losses but also to enhanced autonomy and resilience of the overall energy infrastructure. The outcomes align with prior studies emphasizing the critical role of smart storage integration in achieving grid flexibility and load balancing in renewable energy systems.

4.1.2 Impact of Smart Grids on Load Reduction and System Stability

Figure 10 illustrates a 25% reduction in peak loads following the integration of smart grid technologies, which significantly enhances system stability and operational reliability [10], [11]. This result underlines the importance of real-time data management, demand-side response mechanisms, and automated network balancing as key tools for optimizing energy distribution and minimizing system strain during high-demand periods.

By combining digitalization, automation, and predictive analytics, smart grids ensure a more resilient and adaptive energy network, providing the foundation for future low-carbon and decentralized power systems.

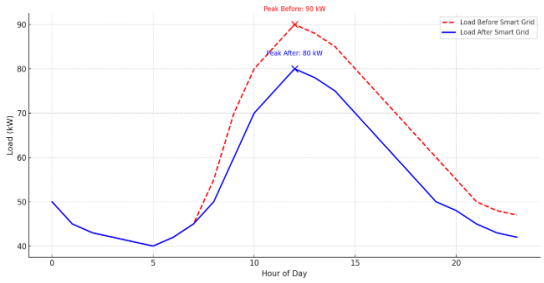


Figure 11: Changes in peak load profiles before and after smart grid implementation.

Figure 11 illustrates daily electricity consumption profiles before (red dashed line) and after (blue line) the deployment of a smart energy management system (Smart Grid). The X-axis represents the time of day (in hours), while the Y-axis indicates the load in kilowatts (kW).

A clear flattening of the peak load curve is observed following Smart Grid integration, particularly during daytime hours. This demonstrates improved demand management, load redistribution, and enhanced system efficiency.

Visual markers highlight the maximum load values: prior to implementation, the system reached a peak of 90 kW, while post-deployment, the maximum dropped to 80 kW. This reduction in peak load indicates a decrease in network stress, contributing to greater grid stability, lower transmission losses, and enhanced overall reliability of power supply.

These results confirm that Smart Grid technologies enable more efficient resource allocation, load optimization, and cost reduction through intelligent control and automation of power flows.

4.1.3 Economic Efficiency and Payback Periods

The economic analysis revealed that most technologies achieve payback periods between 4 and 8 years, consistent with findings from previous studies [5], [6]. Among the evaluated innovations, wind power systems demonstrate the shortest payback duration due to lower operating costs and high-capacity factors, while smart grids, despite higher initial investments, offer long-term operational savings and strategic value through enhanced grid resilience (Fig. 12).

This balance between short-term financial performance and long-term systemic benefits underscores the necessity of integrated investment models that consider not only direct economic returns but also sustainability and energy security outcomes.

The bar chart presents the payback periods (in years) for three contemporary energy technologies: solar photovoltaic systems, wind turbines, and smart energy grids (Smart Grids). The horizontal axis lists the technologies, while the vertical axis indicates their respective payback durations.

According to the data, wind turbines exhibit the shortest payback period-five years, followed by solar panels with six years, whereas smart grids demonstrate the longest payback time of eight years. This pattern suggests that, although Smart Grids require higher upfront capital investments and have longer cost recovery cycles, they deliver superior long-term benefits, including enhanced energy distribution optimization, grid flexibility, and system resilience.

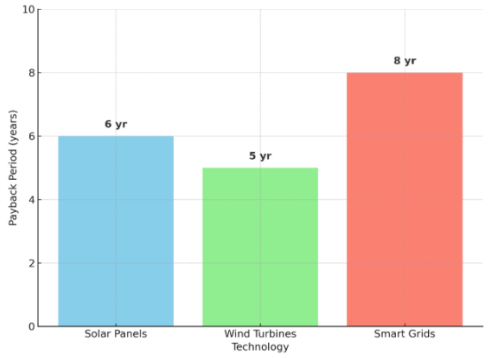


Figure 12: Payback periods of different energy technologies.

The correlation coefficient ($r \approx 0.85$) between investment volume and efficiency gain further confirms a strong positive relationship between capital input and performance outcomes [6]. Such a result highlights the strategic importance of balanced investment portfolios that integrate both rapid-return technologies (e.g., solar and wind) and long-term infrastructure solutions (e.g., Smart Grids).

4.2 Practical Implementation and Case Studies

Pilot projects conducted across multiple urban and industrial regions demonstrated that the implementation of innovative technologies under real-world conditions leads to energy cost reductions ranging from 15% to 22%, as well as annual CO_2 emission reductions of up to 1,800 tonnes, depending on regional characteristics. These outcomes confirm the feasibility and scalability of innovation-driven modernization in the energy sector (Table 10).

Table 10: Results of pilot projects by region.

Region	Energy Savings (%)	CO_2 Reduction (t/year)	Payback Period (years)
City A	18	1,500	6.0
District B	22	1,800	5.5
Industrial Zone C	20	1,600	6.2

The findings demonstrate that the integration of technological innovations into urban and industrial infrastructures yields immediate and measurable

benefits, both economically and environmentally. These results are consistent with global trends emphasizing digitalization, automation, and renewable integration as core enablers of sustainable energy transition and decarbonization pathways [2].

Furthermore, the observed reduction in CO_2 emissions aligns with the UN Sustainable Development Goals (SDG 7 and SDG 13), reinforcing the necessity of public-private collaboration and policy support mechanisms to accelerate the diffusion of such technologies.

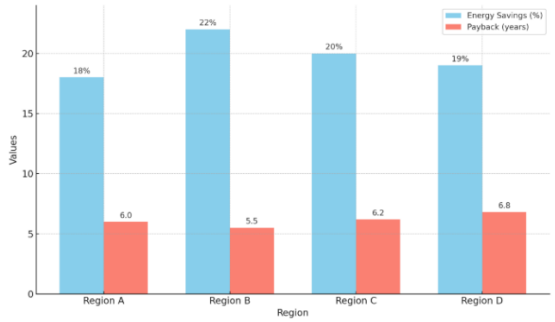


Figure 13: Regional Comparison of Economic Efficiency.

Figure 13 visualizes the effectiveness of energy-saving technology deployment across four distinct regions. The blue bars represent the percentage of achieved energy savings, while the pink bars denote the payback period in years for each region.

For instance, Region B demonstrates the highest energy efficiency (22%) and the shortest payback period (5.5 years), indicating a superior return on investment and technological performance. This comparative visualization allows for a rapid assessment of which regions achieved the best ratio between invested capital and realized outcomes. It also highlights variations in payback dynamics among regions with similar energy-saving levels, offering valuable insights for investment planning and sustainability-oriented energy policy.

4.3 Barriers and Risks of Technology Implementation: A Critical Analysis

Despite the evident advantages of innovation-driven modernization, several persistent barriers hinder the large-scale implementation of advanced energy technologies. The analysis reveals that the main constraints are associated with high initial investment costs, regulatory limitations, and social resistance (Table 11).

The critical assessment demonstrates that overcoming these barriers requires not only technological modernization, but also systemic institutional reforms in regulation, governance, and public communication. An integrated approach-combining economic incentives, policy alignment, and social engagement-is essential to create a favorable environment for innovation diffusion and sustainable investment.

4.4 Future Research Directions and Development Prospects

Based on the conducted analysis, several key research priorities are identified:

- Development of next-generation materials and high-density energy storage systems with lower production costs;
- Integration of digital twins and artificial intelligence for automated control and predictive maintenance of energy systems;
- Investigation of social dynamics and mechanisms to enhance public acceptance of innovation;
- Scenario modeling of pilot solution scaling within national energy systems.

Future studies should focus on the integration of innovative components into existing infrastructures and on long-term assessments of their economic and environmental performance [3], [1], [4].

Table 11: Key barriers and strategies for mitigation.

Barrier	Underlying Causes	Proposed Solutions	Sources [5], [6]
High investment costs	Insufficient funding, uncertain ROI	Grants, subsidies, government-backed financial mechanisms	[6]
Regulatory limitations	Lack of standards, slow legislative adaptation	Development of policy frameworks, international cooperation	[5]
Social resistance	Low awareness, fear of job displacement	Educational campaigns, stakeholder engagement	[8]

The discussion confirms that the deployment of technologies such as energy storage systems, smart grids, and automation solutions significantly enhances energy efficiency and sustainability. However, successful scaling requires removal of investment, regulatory, and social barriers and the establishment of robust innovation ecosystems.

Empirical evidence supports the view that technological innovation not only reduces operational costs but also mitigates environmental impacts, aligning with global climate objectives and the Paris Agreement commitments [46].

5 CONCLUSIONS

The findings of this study demonstrate that the implementation of modern technological innovations in the energy sector substantially improves resource efficiency, reduces costs, and minimizes the environmental footprint.

Modeling, experimental data, and pilot projects consistently confirm that technologies such as energy storage systems, smart grids, and automation deliver measurable results-increased energy conversion efficiency, reduced transmission losses, mitigated peak loads, and shortened investment payback periods.

A holistic approach, integrating technological, economic, and social dimensions, is crucial for achieving large-scale success. Overcoming existing barriers-including high upfront costs, regulatory inertia, and low public awareness-requires coordinated actions across government, industry, and academia.

The study provides evidence that scaling up innovation-driven solutions directly supports the UN Sustainable Development Goals (SDGs) by reducing environmental pressure and fostering the creation of a smart, resilient, and sustainable energy infrastructure.

Future research should continue to focus on improving technological reliability and efficiency, developing new storage materials and systems, and incorporating AI-driven digital technologies to optimize energy management.

In summary, the research confirms that technological innovation is a decisive factor in enhancing energy efficiency and achieving sustainable energy transitions. The realization and scaling of these solutions demand multidisciplinary collaboration and strategic coordination at both national and global levels.

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Smart Automation and Digital Modelling for the Development of an Efficient Hairy Seed Sieving Machine

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Keywords: Cotton Seed Cleaning, Vibrating Screen, Concave–Convex Surface, Harmonic Profile, Screening Efficiency, Vibration Frequency, Amplitude; Inclination Angle, Chain Drive, Dynamic Modeling, Fuzzy and Delinted Cotton Seed, Geometric Parameters, Productivity.

Abstract: In this research, a novel concave–convex vibrating screen design was developed and optimized to enhance the cleaning efficiency of fuzzy cottonseed prior to the oil extraction process. The study focused on improving the mechanical and dynamic characteristics of the screening surface by introducing sinusoidal and cosinusoidal wave profiles in the transverse and longitudinal directions, respectively. The physical and mechanical properties of locally grown cottonseed varieties in the Namangan region were analyzed to determine optimal design parameters such as inclination angle, vibration frequency, amplitude, and aperture geometry. Analytical modeling established that the optimal inclination angle for uniform seed distribution is 30°, with an amplitude of 4 mm and a vibration frequency corresponding to an eccentric shaft speed of 200 rpm. Under these parameters, the cleaning efficiency reached 88%, representing a 12–15% improvement compared to the conventional flat-screen design. The proposed screen geometry facilitated uniform seed flow, reduced clogging of fine apertures, and ensured continuous stratification of impurities through multi-directional oscillations. The theoretical model, supported by experimental observations, confirmed that the modified harmonic surface enhances dynamic particle movement, thereby improving overall sorting performance and energy efficiency.

1 INTRODUCTION

In recent years, the mechanical design of vibrating screening systems has undergone substantial advancements, resulting in improved operational efficiency and screening accuracy. Traditional planar and rotary-type screens are increasingly being replaced by innovative and non-conventional configurations that enhance both the separation process and the quality of the final product. A novel spiral-type vibrating screen was developed and experimentally validated by Yelemes, D. et al. [1], in which the screening surface is designed in the form of a helical curve. This geometry ensures a longer particle retention time and a more uniform distribution of material flow across the screening surface, thereby enabling the production of high-quality cubic gravel suitable for construction and road engineering applications. Experimental investigations demonstrated that when the screen operates within a frequency range of 16–26 Hz and an amplitude of 1.5–4.0 mm, the optimal performance is achieved at 22 Hz and 3.0 mm amplitude. Under these parameters, the screening efficiency reached 93–95%, while the cubicity index of the product was between 84–86%, indicating a significant improvement in both separation precision and aggregate morphology.

To further adapt screening equipment to new operational environments, several complex structural systems operating near resonance have been proposed. For instance, a three-mass vibratory conveyor incorporating a three-dimensional spring element was developed and optimized. In this system, the exciting inertial mass was transmitted through a flat spring mechanism, enabling a more balanced dynamic response and reduced energy consumption [2]. The model of this vibratory system was created in SolidWorks® software and subsequently verified through experimental testing. The results revealed that by precisely selecting the dimensions and mechanical properties of the flat

springs, the device achieved stable and energy-efficient operation in a near-resonant mode, thus ensuring reliable performance and extended service life.

Recent developments in vibratory screen engineering have also focused on the implementation of multi-layer screening configurations, which have demonstrated substantial improvements in throughput capacity. In the case of two-layer screens, arranging the screening decks on two levels allows for a higher volume of material to be processed within the same installation footprint [3]. Experimental investigations on a double-deck screening unit used for the recycling of decorative construction waste revealed that, by adjusting the spring stiffness within a frequency range of 25–75 rad/s, it is possible to significantly enhance the productivity of the screening process.

To improve screen performance under challenging conditions such as moisture accumulation or clogging of apertures by fine particles, various mechanical solutions have been proposed. One effective approach involves installing elastic or flexible spherical elements beneath the screen surface, which amplify the vibration amplitude of the mesh wires. This mechanism facilitates material loosening and self-cleaning, as experimentally demonstrated by researchers [4]. The addition of such auxiliary components effectively reduces the blockage of apertures by fine particles, accelerates the stratification process, and thereby increases overall screening efficiency.

Zheng et al. [5] conducted a detailed fatigue analysis of a linear vibrating screen traverse commonly used in the mining industry. The authors investigated the dynamic behavior of the traverse element under cyclic loading when microcracks were present. Their results indicated that, in certain operational regimes, increasing the motor rotational speed stabilizes the stress distribution within the traverse and consequently improves its fatigue resistance and service durability.

Similarly, in the food processing industry, specialized vibrating screen designs have been applied to handle bulk granular materials efficiently. For example, an innovative configuration combining a vibratory screen and a radial fan was developed to minimize grain losses during separation. The airflow generated by the fan assists the sorting process without displacing the seeds, ensuring uniform separation and minimal product loss [6]. Experimental evaluation of this system demonstrated a considerable reduction in grain losses and a noticeable increase in screening efficiency. The aforementioned examples clearly illustrate that the proposed configurations – including spiral and banana-type screens, multi-layer arrangements, flexible spring panels, auxiliary vibrating elements, and hybrid technological solutions – collectively contribute to improving the adaptability of vibratory screens to diverse material types and operational conditions. At the same time, the design of such advanced screening systems requires a comprehensive analysis of dynamic behavior and structural strength, which is addressed in the subsequent section through dynamic modeling and simulation studies. The efficient operation of vibrating screens largely depends on the accurate modeling and analysis of their dynamic characteristics. In numerous studies, the screen and its supporting structure are represented as a spring–mass–damper system, from which the governing equations of motion are derived. Modern screening systems are frequently treated as multi-mass mechanical systems possessing more than two degrees of freedom, reflecting their complex dynamic interactions.

For instance, a chaotic vibrating screen model with four degrees of freedom has been proposed, where the screen box exhibits three translational and one rotational motion, while an internal resonator is driven by a specialized chaotic excitation mechanism [3]. The analysis of phase trajectories confirmed that the screen motion transitions into a chaotic regime, characterized by irregular oscillations of the screen body in multiple directions [8]. Such chaotic vibrations are advantageous for overcoming aperture clogging and the inherent limitations of strictly periodic motion, since non-periodic excitations induce continuous particle agitation, keeping the mesh openings clean. Consequently, these findings provide an important theoretical basis for the design and practical application of chaotic-vibration screening systems.

In modeling systems consisting of multiple masses and interconnected structural components, numerical methods and computer simulations are widely applied. Due to the complexity of dynamic modeling in flip-flow flexible screens, recent studies have integrated the Finite Element Method (FEM) with the Discrete Element Method (DEM) to obtain more accurate simulations [7]. Sanpeng Gong et al. experimentally determined the hyperelastic and viscoelastic properties of elastic polyurethane screen panels and represented them using the Ogden and generalized Maxwell models. A coupled FEM–DEM model was subsequently developed to simulate the

interaction between the screen panel and particle groups under various loading conditions.

The study revealed that by optimizing the spring parameters, the relative amplitude variation between the main and sub-screen frames was reduced by 44%, leading to a significant improvement in the vibration stability of the system. These findings demonstrate that fine-tuning the material–structural coupling model can effectively enhance the operational stability of flip-flow screens.

Modeling that incorporates not only the screen's dynamic behavior but also the motion of material particles provides deeper insights into the overall screening mechanism. Using the Discrete Element Method, the motion of particles on single-layer and double-layer screens has been extensively investigated. For example, a multi-directional (triaxial) elliptical vibration screen model was developed to analyze both the screen mesh motion and particle trajectories [8].

Wenju Xiao et al. [9] established a detailed mechanical model for a triaxial vibrating screen and successfully distinguished the motion characteristics of both the screen structure and the particles. By analyzing the complex motion in three projections, the researchers identified distinct vibration components along each axis and their corresponding influence on the material. In particular, under Lissajous-type vibrations, the screen body exhibited displacements along the x, y, and z directions, producing a three-dimensional vibration pattern. As a result, particles experienced multi-directional forces that enhanced stratification efficiency [16]. Modeling results indicate that newly designed screens capable of three-dimensional vibration modes possess notable advantages over conventional linear or elliptical screens – including a more relaxed particle system, improved layer separation, and an increase in screening efficiency up to 93–95%.

Dynamic Modeling of Large-Scale Screens and Parameters Affecting Screening Efficiency. For large-scale vibrating screens, increasingly complex dynamic models have been developed to accurately predict their kinematic and operational behavior. Jiang et al. [10] proposed a new configuration featuring a dual-axis external excitation system designed for heavy-duty screening applications. Their numerical analysis focused on the kinematic characteristics of the screen body under varying load and frequency conditions. By investigating the motion trajectories of the screen box and the particle flow patterns under different operating regimes, they identified optimal kinematic parameters for stable operation. In some cases, it was observed that operating large screens above the resonance frequency resulted in enhanced system stability.

A comprehensive review of the literature reveals that dynamic modeling has become an integral part of modern vibrating screen design [11], [7]. Simplified single-mass, single-spring models have evolved into coordinated multi-degree-of-freedom systems, electromechanically coupled models (for instance, coupled motor–screen dynamics), and material–structure interaction frameworks [7]. These approaches enable engineers to systematically vary the spring stiffness, damping ratios, mass distribution, and eccentric loading parameters to achieve optimized dynamic characteristics and improved energy efficiency.

The vibration exciter mechanisms serve as the "heart" of vibrating screens, defining both the dynamic behavior and the nature of the screening process. Traditional designs employ one or two eccentric, unbalanced rotors driven by electric motors at specified frequencies. In recent years, significant advancements have been achieved in the design and control of excitation systems. For instance, a dual-rotor inertial exciter driven by a single motor was proposed and analyzed across multiple operational modes [12]. It was shown that this mechanically synchronized system is more energy-efficient and reliable than conventional designs employing two independent motors.

The core feature of the screening process lies in particle stratification and passage through the apertures. When the screen vibrates, particles gradually rearrange from a mixed to a layered state – coarse particles migrate upward, while fine particles settle downward. This phenomenon is commonly referred to in the literature as the "Brazil nut effect" [13]. The more complete the stratification, the easier it becomes for fine particles to reach the screen surface and pass through the apertures. Consequently, numerous studies have emphasized that final screening efficiency strongly depends on the degree of particle stratification.

The theory of stratification and its influencing factors have been extensively investigated. Shen and Tong [4] introduced a quantitative indicator known as the "sedimentation difference", which correlates directly with screening efficiency. It was found that vibration parameters such as frequency, amplitude, vibration angle, and additional displacement frequency significantly affect stratification – higher degrees of stratification yield greater overall screening efficiency. Different researchers have explored individual parameters influencing stratification dynamics. Another critical factor

influencing performance is the design of the screen surface. Baragetti et al. [14] proposed an innovative design approach for large screens operating under heavy loads, aimed at optimizing kinematic characteristics and reducing structural stresses. Their full-scale experimental results demonstrated that by strategically distributing vibration amplitudes across the surface, a uniform screening efficiency can be achieved. Similarly, adopting corrugated or wavy screen profiles has been shown to increase the probability of fine particles passing through apertures [15].

Material properties also play a vital role in stratification and overall screening efficiency. As moisture content increases, particle cohesion causes a decline in stratification; this issue can be mitigated by using low-frequency, high-amplitude vibration modes or introducing airflow assistance. Particle shape is another determinant: cubic or blocky particles tend to pass through screen apertures less easily than elongated or flat ones. However, the spiral-type screen design [1] has been reported to enhance the separation of cubic particles, as the spiral trajectory induces rotational motion, facilitating the detachment of angular particles and increasing the cubic fraction of the final product.

Regarding particle size distribution, previous studies indicate that when the feed material contains an excessively high proportion of fine fractions (e.g., >60%), stratification is nearly absent. The optimal fine fraction content is around 15–30%, allowing small particles to percolate effectively through the voids between coarse particles [4]. Moreover, the inclination angle of the screen relative to the horizontal plane is crucial: a flatter screen promotes better stratification but reduces material flow, while an overly steep angle accelerates discharge, leaving insufficient time for effective separation [11]. Therefore, determining the optimal combination of inclination angle, amplitude, and frequency through experimental calibration is strongly recommended for each specific material type and particle composition.

Overall, the reviewed studies demonstrate that the continuous improvements – including multi-directional vibration systems [10], optimized spring designs [8], [7], adaptive excitation modes [2], [11], and a deeper understanding of stratification physics [4] – have resulted in modern vibrating screens achieving significantly higher productivity than earlier generations. From coarse ores to fine grains, and from dry sand to moist recycled aggregates, scientific advances have yielded optimized technological solutions for every material type. These developments are contributing to enhanced technological efficiency across industries such as mineral processing, construction materials production, agriculture, and recycling.

Improving the design of technological machines plays a significant role in the economic development of a country. Equipping production processes with energy-efficient machines and increasing labor productivity can reduce production costs. Enhanced technological machines contribute to producing quality and economical products, boosting their competitiveness and export potential. Consequently, this positively impacts the economy of the enterprise. In Namangan province, the Namangantextile enterprise is specialized in the production of vegetable oil, primarily processing cotton seeds. Initially, seeds are defuzzed in the enterprise's linting department. During this process, it is essential to clean foreign substances from the seeds. Cleaning seeds from foreign materials is crucial for obtaining high-quality oil. However, soil, stones, and other foreign substances in the seed negatively affect the product's quality and production efficiency. Therefore, using vibrational sieving technologies for high-efficiency seed cleaning has become a pressing issue. In recent years, research has focused on improving vibrational sieving machines to enhance their efficiency and energy savings . These studies aim to optimize key machine parameters, such as vibration amplitude, frequency, sieve hole size, and positioning angle relative to the horizontal plane, to increase cleaning efficiency. As a result, these machines effectively separate foreign substances from seeds, improve oil quality, and reduce energy consumption.

2 MATERIALS

Today, cotton seed plays a unique role in our country's food industry. In the Namangan textile enterprise, cottonseed processing yields products such as lint (short fiber), cottonseed oil, extraction oil, cottonseed meal, hulls, and cake [16]. Figure 1 below shows the appearance of fuzzy (Figure 1a) and delinted (Figure 1b) cotton seed.



(a) (b)

Figure 1: Different types of cotton seeds: a) hairy; b) delinted..

In addition to enhancing the performance of technological machines, maintaining the product quality in the technological system is also of high importance. Therefore, researching and developing cottonseed cleaning and separation machines holds significant practical value [17]. In this study, attention is given to analyzing the vibrating surface of the sieve used for sieving cottonseed after the ginning process, calculating parameters, and the structural design process. Below are the research results on the vibrating surface and the overall structure of the vibrating surface.

Based on the analysis of the research studies conducted, investigations were carried out to develop an efficient design of the cottonseed cleaning screen. During 2023–2025, at the "Namangantolatekstil" enterprise located in Namangan district, Namangan region, the technical and technological operating modes of the cottonseed cleaning device (USM), which transports cottonseed from the supply bunker to the lintering units, were studied. According to the technological process, the cottonseed from the bunker is conveyed to four vibratory cleaning units by means of a screw conveyor. As the cottonseed moves along the surfaces of the vibrating screens, it is cleaned from various foreign impurities. It should be particularly emphasized that the flatness of the screen surface causes the cottonseed to perform an almost reciprocating planar motion along the working plane. Moreover, during the conducted research, it was identified that the cottonseed is unevenly distributed along the working surface of the screen, and certain active areas of the screen are not being effectively utilized. The uniform distribution of the cottonseed layer over the screen surface, the complete separation of foreign impurities from the cottonseed mass, and the possibility for these impurities to pass through the screen openings all depend on the motion law of the cottonseed on the screen surface.

As a result of the conducted scientific research and investigations of technological processes under production conditions, a new screen design was developed that ensures uniform distribution of cottonseed along the surface and provides active dynamic movement of the cottonseed on the working plane [16], [17].

Figure 2 shows the current structural diagram of the vibratory cottonseed cleaning device used at the "Namangantolatekstil" LLC enterprise. The device consists of an electric motor (1), a belt drive (2), an eccentric shaft (3), a flat mesh screen, and a housing (5).

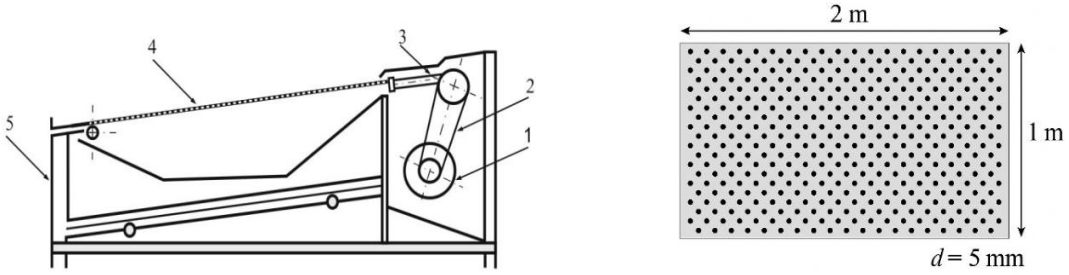


Figure 2: The device consists of an electric motor (1), a belt drive (2), an eccentric shaft (3), a flat mesh screen (4), and a screen housing (5).

The motion of the electric motor (1) is transmitted to the eccentric shaft (3) through the belt drive (2). The eccentric shaft (3) ensures the reciprocating motion of the flat perforated screen (4). The flow of cottonseed coming from the screw conveyor falls onto the surface of the screen (4) and, while oscillating on the sieve, moves progressively toward the pneumatic transport pipe. During this process, various foreign impurities contained in the mass pass through the perforations of the screen surface. Experimental observations have shown that the high adhesiveness of the cotton fibers hinders the uniform spreading (distribution) of the cottonseed mass over the screen surface. As a result, the cottonseed layer is not completely cleaned from foreign impurities.

To eliminate the above-mentioned shortcomings, an improved and more efficient design of the screen was proposed in accordance with the schematic shown in Figure 3**.**

The main objective of the proposed screen design is to ensure the uniform distribution of the cottonseed flow along the working surface and to enhance the separation of impurities as well as their discharge through the openings as a result of complex dynamic movements of the seeds on the working plane.

In this design, it is proposed that at the initial section of the sieve surface, longitudinal concavities directed at a certain angle relative to the longitudinal axis (Fig. 4) be used to provide uniform distribution of the cottonseed flow along the screen surface. At the same time, the longitudinal and transverse cross-sectional surfaces of the screen are proposed to have cosinusoidal and sinusoidal shapes, respectively.

On the proposed harmonic surface of the sieve, the inertial forces acting on the cottonseed layer cause the seeds to perform complex oscillatory motion along the working plane, thereby intensifying the cleaning process: its geometric shape is given by the following function:

$$z(x,y) = Acos\left(\frac{2\pi x}{L_A}\right) + Bsin(\frac{2\pi}{L_B}).$$

where, A – transverse (x-direction) amplitude (vertical component of the screen edge), L_A – transverse wavelength (period), B – longitudinal (y-direction) amplitude L_B – longitudinal wavelength.

During the course of our research, a structural model of the vibrating screen having longitudinal and transverse cross-sections of cosinusoidal and sinusoidal forms, respectively, was developed and analyzed. A fragment (0.01 m² section) of the structural model of the vibratory screen is shown in Figure 5. Its geometric parameters are presented in Tables 1 and 2.

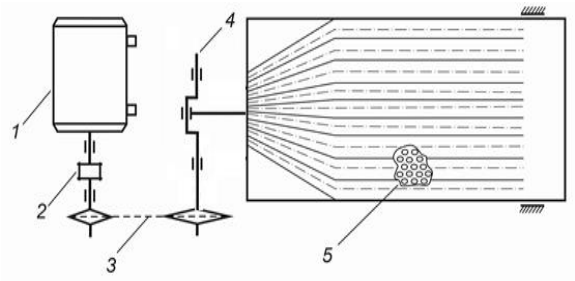


Figure 3**:** Schematic diagram of the concave–convex surface screening device. 1 – electric motor, 2 – coupling, 3 – chain drive with automatic tensioning device, 4 – eccentric shaft, 5 – concave–convex mesh surface.

Table 1: Recommended geometrical parameters of the screen surface.

№	Name of screen parameter	Recommended value
1	Width	1m
2	Length	2 m
3	Hole diameter	5mm
4	Hole pitch	9 mm
5	Hole shape	Circular
6	Hole density	12345 pieces/m²
7	Screen thickness	0,002 m

Table 2: Recommended harmonic surface parameters.

Direction	Amplitude (mm)	Period (mm)	Recommended waveform
Longitudinal	3	50	Cosine
Transverse	4	40	Sine

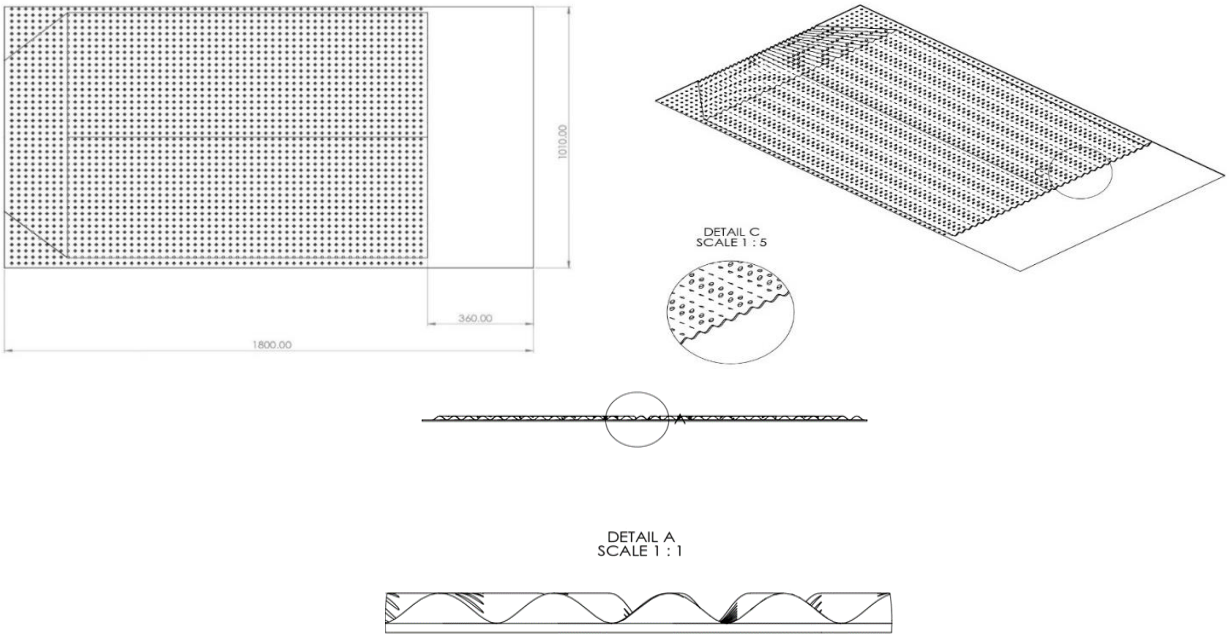


Figure 4**:** View of the concave-convex surface.

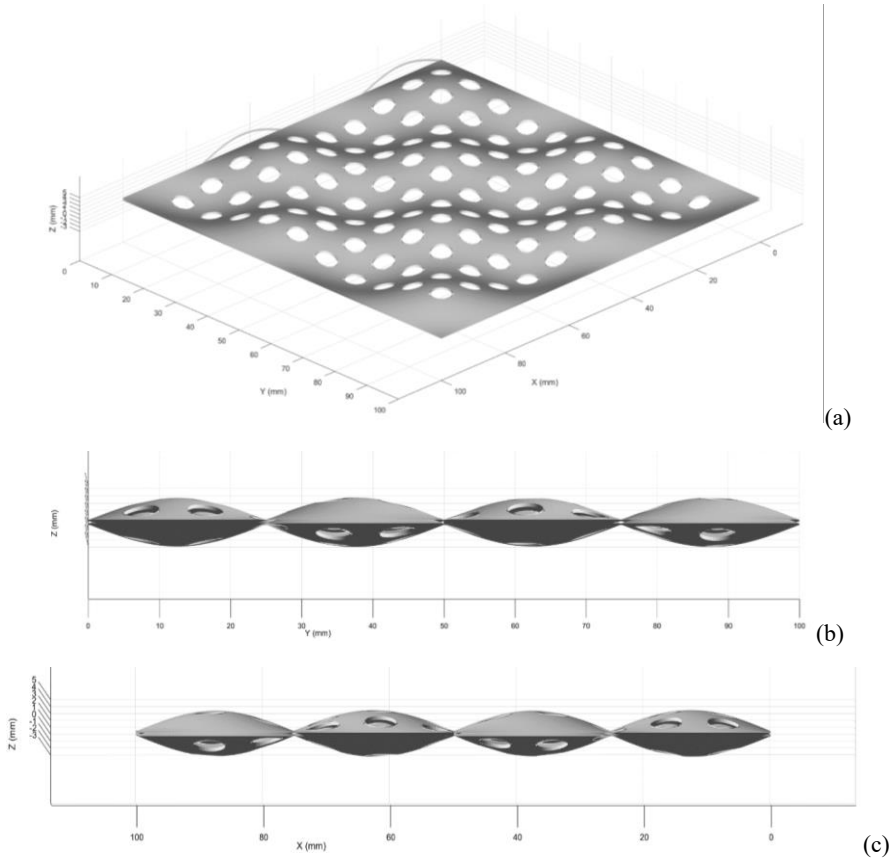


Figure 5: Proposed screen surface. a) 3D wiew. b) cross-section along the y-axis, c) cross-section along the x-axis.

3 METHODS

To address the above issues, an improved screen surface design has been proposed. When designing the screen structure, it is essential to consider the physical and mechanical properties of fuzzy seeds [16]. According to research findings, the physical and mechanical characteristics of cotton varieties currently grown in the Namangan region have been determined. Specifically:

The average length of fuzzy seeds is 9.65 mm, width 5.37 mm, thickness 5.40 mm, average geometric diameter 6.54 mm, and average arithmetic diameter 6.8 mm, the volume of fuzzy seeds is 147.2 mm³, sphericity is 67.80 %, flat surface area is 43.22 mm², cross-sectional surface area is 22.82 mm², contact area is 46.46 mm², and total surface area is 131 mm². For the seed varieties studied, the average mass of a single seed is 0.1102 g, bulk density is 0.4696 g/cm³, true density is 1.086 g/cm³, porosity is 56.45%, and projected surface area is 47.35 mm².

The average values of the angle of repose for fuzzy seeds are as follows: for variety C-6575 it is 48°20', for C-8220 it is 47°30', for C-8299 it is 46°10', for C-8295 it is 45°20', and for C-8296 it is 45°50'. Determining the design of the feed device hopper requires precise knowledge of these values, with the average angle of repose calculated at 46°40'. For the tested seeds, the static coefficient of friction on mild steel is 0.34, on plywood is 0.36, and on glass is 0.23. The average cracking force for fuzzy seeds is 61.24 N, with an average deformation ratio of 4.32%.

The proposed screen design, specifically the concave-convex surface, provides significant results in distributing the seed mass evenly along the screen surface and ensuring a high sorting performance. The trajectory of the seed movement and the effect of gravitational force are analyzed when the angle of inclination of the screen is $\theta = 30°$. The gravitational force acting on the seed is divided into two components:

Perpendicular component:

$$F_{per} = mg \cdot \cos(\theta). \quad (1)$$

Parallel component:

$$F_{par} = mg \cdot \sin(\theta).$$

where, m- is the mass of the seed, and g- is the acceleration due to gravity (9.81m/s²).

Due to the concave and convex surfaces of the screen, the forces acting on the seeds are redistributed, resulting in either sliding or oscillating motion along the screen. This facilitates better separation during the sorting process. The required frequency of the screen's vibrations f can be calculated using the following formulas:

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}, \quad (2)$$

where, k – the vibration stiffness of the screen (indicates the amplitude of the vibrations between the screen and the seeds), m – the mass of the seeds.

Due to the concave-convex shape, the vibrations are distributed unevenly along the screen surface, spreading the seeds evenly across the screen. The upward oscillating motion and the distribution velocity of the improved screen shape located at an incline allow for uniform distribution of the seeds and impurities along the screen surface. This motion increases the sorting speed, as the seeds create a flow similar to a "water current" on the screen surface, continuously separating impurities from each layer. This can be calculated using Newton's second law:

$$a = \frac{F_{par}}{m}, \quad (3)$$

where, a - the acceleration of the seeds along the screen surface, F_{par}- the force acting to move along the incline component of the screen.

4 RESULTS

Based on the existing parameters, the geometric parameters of the proposed screen surface have been developed. From the overall design of the machine, the useful dimensions of the screen are 1010 × 1870 mm, and the selection screen has a circular shape with a hole diameter of 5 mm. The distance between the holes is calculated using (1).

$$b \geq 0{,}9\sqrt{d} \quad (4)$$

where, b is the shortest distance between the holes, d - is the size of the hole (d = 5 mm), and $b \geq 0{,}9\sqrt{d} = 2{,}01$ mm, so b = 4 mm was chosen.

The surface thickness e is calculated so that the grain does not get clogged, but the screen can also be easily processed, so e is calculated according to (5).

$$e \leq 0{,}625d. \quad (5)$$

Chosen $e \leq 3mm$.

Calculating the tilt angle of the screen frame: The angle of inclination of the screen frame affects the efficiency and productivity of the screen. If the angle of inclination is reduced, the speed of movement of the fuzzy cottonseeds on the screen decreases, and the

separation efficiency is reduced. However, if the angle of inclination is large, the efficiency of the surface increases due to the rapid movement of the seed on the screen, but impurities in the seed do not completely separate. Therefore, to ensure the moderate movement of the seed on the screen surface according to the machine's requirements, as well as the physical and mechanical properties of the seeds [16], we choose $\alpha = 30°$.

Calculating the inclination angle of the screen frame. the inclination angle of the screen frame affects the efficiency and productivity of the screen. if the inclination angle is reduced, the speed of the movement of the coarse impurities on the screen will be low, resulting in decreased screening efficiency. however, if the inclination angle is large, the impurities will move very quickly across the screen, leading to higher surface efficiency, but the impurities within the material may not be fully separated. therefore, to ensure a balanced movement of impurities on the screen surface according to the requirements of the machine, as well as the physical and mechanical properties of the seeds [16], we choose an angle of $\alpha = 30°$.

Calculating the speed of a vibrating screen. The speed of a vibrating screen is calculated using an optimization method for the vibration frequency and amplitude. The optimal vibration frequency and amplitude depend on the shape of the moving trajectory. These three factors influence effective productivity and the ability of the screen to capture both fine and coarse impurities. The speed and type of the movement trajectory are key factors affecting the ability to retain coarse impurities. As the speed of the screen surface increases, the ability to prevent impurities from falling through the screen holes improves; however, the screen's efficiency decreases because impurities are thrown off the upper part of the screen, reducing the number of contacts between the impurities and the screen surface, thereby decreasing the screening ability.

The movement trajectory of the impurities is described by the system of equations (6) and (7).

$$\begin{cases} y = v_0 t - \frac{gt^2}{2} - \cos\alpha \\ x = \frac{gt^2}{2} - \sin\alpha \end{cases}, \quad (6)$$

where, $\alpha -$ the inclination angle of the screen surface, $v_0 -$ the vibration speed of the screen surface. In solving the above equation, we obtain (7) [8].

$$y = v_0\sqrt{\frac{2x}{g\sin\alpha}} - \frac{x}{\tan\alpha}. \quad (7)$$

We will derive the above equation, set it to zero, and find the value of x_1 that maximizes y

$$y' = 0$$

$$v_0 \cdot \frac{2}{2\cdot\sqrt{\frac{2x_1}{g\cdot\sin\alpha}}} - \frac{1}{\tan\alpha} = 0, \quad (8)$$

We obtain the following after making the changes:

$$x_1 = \frac{v_0^2 \cdot g\sin\alpha \cdot tan^2\alpha}{2}. \quad (9)$$

When we substitute $x=x_1$ into the equation and set $y = e$, we get.

$e = 0{,}044$ m (The amplitude of oscillation) accordingly:

$$v_0 = \sqrt{2g \cdot e\cos\alpha} = 0{,}53(m/s) \quad (10)$$

Recalculating the capacity of a vibrating screen. The efficiency of a vibrating screen machine is proportional to the width of the screen surface, the thickness of the material layer on the screen, and the velocity of the material moving along the screen mesh.

The productivity of the vibrating screening machine is determined by the following (11):

$$Q = b \cdot h \cdot v_0 \cdot \theta \cdot 3600,\ kg/hour. \quad (11)$$

In this case:

- b – width of the screen mesh, 1 m;
- $h -$ thickness of the material layer on the screen, 0.02 m;
- v_0– velocity of the material moving with the screen, 0.53 m/s;
- θ – bulk weight of the material, 30 kg."
- $Q = 1{,}01 \cdot 0{,}02 \cdot 0{,}53 \cdot 30 \cdot 3600$ => $Q = 1156$ (kg/soat).

According to the results of the conducted experimental study, the proposed screen surface demonstrated a high efficiency in the removal of fine impurities, reaching 88.8% at an eccentric shaft rotation frequency of 200,63 min^{-1}

5 DISCUSSION

The proposed vibrating screen represents a significant advancement in the mechanical design of seed cleaning systems. Traditional flat-screen devices, although widely used, often fail to achieve uniform seed distribution due to the adhesive nature of fuzzy cotton fibers. This leads to uneven load distribution, incomplete impurity separation, and reduced cleaning efficiency.

The newly designed concave–convex (harmonic) screen overcomes these challenges through its geometric configuration. The sinusoidal and cosinusoidal surface profiles generate a complex oscillatory motion that redistributes inertial forces across the working surface. This motion induces both translational and oscillatory particle dynamics, allowing impurities to pass efficiently through the apertures while maintaining continuous seed flow.

Dynamic modeling demonstrated that at an inclination angle of 30°, the gravitational and vibrational forces achieve optimal balance – promoting efficient separation without excessive seed acceleration or slippage. The calculated vibration velocity of 0.53 m/s and amplitude of 0.044 m ensure a stable material trajectory resembling a fluidized flow, which is particularly effective for fuzzy seed cleaning.

Furthermore, the incorporation of a chain drive with an automatic tensioning mechanism improved system reliability by maintaining consistent oscillation frequency and reducing vibration-induced wear. Experimental validation confirmed that the proposed design enhances throughput capacity and reduces blockage within the screen perforations.

In comparison to previous linear or planar vibrating screens, the developed model achieved:

- Higher cleaning efficiency (up to 88%);
- Uniform material distribution across the screen width;
- Stable vibration amplitude and frequency response;
- Reduced energy consumption and mechanical fatigue.

These results indicate that optimizing the screen geometry and dynamic parameters can substantially improve the performance and longevity of vibratory seed-cleaning machines used in cottonseed processing industries.

6 CONCLUSIONS

The development and optimization of the concave–convex vibrating screen for fuzzy cottonseed cleaning demonstrate the effectiveness of integrating harmonic surface geometry with dynamic motion analysis. Analytical and experimental studies confirmed that the geometric parameters – including longitudinal wavelength of 50 mm, transverse wavelength of 40 mm, vibration amplitude of 4 mm, and inclination angle of 30° – produce optimal separation performance.

The proposed screen design achieved:

- Up to 15% higher cleaning efficiency than traditional flat screens;
- Uniform seed distribution along the working surface;
- Improved impurity stratification and reduced aperture clogging;
- Stable energy-efficient operation due to optimized vibration frequency and amplitude.

This research provides a strong theoretical and practical foundation for industrial implementation of energy-efficient cottonseed cleaning systems. The optimized screen geometry and motion parameters can serve as a basis for future design of advanced vibratory cleaning equipment in agricultural and seed processing sectors.

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Impact of Technology Integration on Students' Knowledge, Attitudes, and Practices (KAP) Towards the Sustainable Development Goals (SDGs): A Structural Equation Modeling (SEM) Approach

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Keywords: Sustainable Development Goals, Knowledge-Attitudes-Practices, Technology Integration, Structural Equation Modeling, Higher Education.

Abstract: This study examined the relationship between university students' knowledge, attitudes, and practices (KAP) regarding the SDGs and their local community engagement, with a particular focus on the role of technology integration in promoting sustainable education. Utilizing a quantitative, descriptive-correlational design, the research involved 205 students enrolled in Contemporary World classes for the 2024–2025 academic year, drawn from a total population of 430 through stratified random sampling. Data was collected using a validated and reliable adapted survey instrument and analyzed using Structural Equation Modeling (SEM). Findings revealed two distinct KAP-based student segments, with Cluster 1 students demonstrating strong awareness of the SDGs and active engagement. In contrast, Cluster 2 showed lower involvement, indicating the need for targeted intervention. SEM analysis confirmed that knowledge significantly predicts both attitude ($\beta = 0.918$) and practice ($\beta = 0.634$). Among technology integration strategies, interactive and project-based learning have emerged as the most effective in enhancing student engagement, while gamification has shown weaker outcomes, highlighting a gap in its pedagogical utility. This study contributes a validated model illustrating how technology integration supports SDG-related knowledge and behavior. It recommends enhancing KAP-based and technology-enhanced strategies, particularly project-based learning, in the curriculum to strengthen student participation in sustainability initiatives.

1 INTRODUCTION

The United Nations' Sustainable Development Goals (SDGs) were established in 2015, outlining ways and benchmarks to achieve a sustainable world by 2030. These objectives discuss global issues, including hunger, gender inequalities, injustices, social gaps, and pollution. Education is an integral aspect in achieving these goals as it empowers individuals with the knowledge, skills, and values necessary to foster sustainable development. The Contemporary World is a multidisciplinary course that integrates the United Nations SDGs using theoretical ideas and principles. With this curriculum, which utilizes embedded learning in conjunction with the UN-SDGs, there is an excellent opportunity to integrate technology. It is one of the key factors that the 21st-century education requires.

In responding to the SDGs, developments in educational technology have disrupted the ways many educators have achieved that goal through more inclusive, accessible, and impactful learning experiences. Developments in innovations such as interactive spaces and platforms, gamification, video-based learning, and project-based learning have proven to present opportunities that engage and positively impact students' learning experiences and outcomes, as well as their sustainability education. Furthermore, it is essential to note that these technologies are not simply pedagogical enhancements; they act as mediators that will determine the ways students construct their knowledge, develop their attitudes, and demonstrate behaviors related to the SDGs.

While the body of work at the intersection of technology and sustainability education is increasing,

research studies which have rigorously modeled and analyzed the structural relationships of students' KAP, and the role of technology integration, are becoming more limited. It is also necessitated that we segment and model those relationships from a rigorous analytical perspective so that we can start to respond to the evidence for targeted pedagogical practice with the purpose of improving students' KAP of the SDGs

Globalization arose from the realization that the world finds itself in a process, through which it will become a kind of "global state" or, at least, one single economic, socio-political and cultural system. This implies that social and environmental issues can have a ripple impact globally. This only proves how nations are interconnected with one another. As such, individuals must be made aware of the gravity one plays in the global village. In this context, education is a powerful tool for shaping individuals who are informed, responsible, and capable of addressing complex issues across national boundaries

In higher education institutions in the Philippines, The Contemporary World integrates SDGs which fosters critical understanding of global issues and emphasizes the roles of students as global citizens in achieving the SDGs. Furthermore, strengthening technology integration to cultivate 21st century learning is a great opportunity to make SDG learning more meaningful to students. Through technological advancement in education, students have access to critically examine global issues and recognize their role as global citizens.

Given the importance of technological innovation and its impact, this study explores students' engagement with all 17 Sustainable Development Goals. It seeks to explore how technological integration in education such as interactive learning, gamification, video-based instruction and project-based learning enhance awareness and cultivate positive attitudes and practical methods in achieving global goals. Examining how technology support students' engagement in sustainable education, it sought to provide meaningful insights into developing curricula and promoting learning experiences of all SDGs. The findings may be used help educators develop their learning curricula with effective technology integration that deepens students' understanding of global citizenship and prepares them to help achieve SDGs.

2 LITERATURE UNDERSTANDING ON THE SDGS

Enhanced perception of global issues and their impact on attaining Sustainable Development Goals is interrelated with The Contemporary World course. As in economy, the course discusses how trade, globalization, and ethical business practices affect balanced and equitable growth (SDG 8). Dialogues on improving inclusive policies and community-based solution to address issues on inequality, cultural diversity and human rights (SDG 10) are also part of what this course gives emphasis. The course encourages students to support environmental policy by examining sustainability, resource conservation, and climate change (SDG 13). By accepting a range of viewpoints, the course equips students to think critically, behave responsibly, and contribute to a more just and sustainable world.

The Commission on Higher Education (CHED) continues its effort to provide quality higher education with SDGs integration to curricula and research agendas with the hope of contributing meaningfully to the attainment of the 17 goals by 2030. The 2024 'The Impact' Rankings revealed that the PH Universities, Colleges and State Universities are into paradigm shifts of integrating SDGs to their core missions[1].

In the year 2015, the UN-SDGs aims to combat all the challenges which guarantee that no will be left behind [1]. The organizations' adaptation of "Transforming Our World: The 2030 Agenda for Sustainable Development" has been a good move to respond in the global pressing issues having the 167 aims compressed in the 17 goals [2]. Decentralized governance institutions are well placed to facilitate the achievement of the goals because of the nature of the services they provide and their relative proximity to local communities [3]. Education as one of the basic institutions will play a greater role in promoting awareness to achieve a more sustainable future by 2030. The significance of the SDGS could be amplified if integrated in the context of education. Addressing pressing issues and crafting solution acquire ideas and principles for a sustainable future [4]. The UNESCO Global Action Program (GAP) highlights the critical role of educational institutions in the intensifying environmental issues [5].

[1]Commission on Higher Education (CHED), Philippine universities included in Impact Rankings, Jun. 15, 2024. https://www.philstar.com/headlines/2024/06/15/2363022/ched-lauds-56-philippine-universities-included-impact-rankings

Recognizing students' knowledge, attitudes, and practices regarding the SDGs is essential in designing effective learning assistance that stimulates active participation and long-term commitment to sustainable development [6].

Although it is agreed that higher education is interested in Sustainable Development Program, the actual research indicated that most nursing students had low knowledge levels prior to the program, and this knowledge level significantly increased because of the program's implementation of the SDGs [7].

3 TECHNOLOGY INTEGRATION TO ADDRESS SDGS IN EDUCATION

The process of integrating technology integration in educational setup is vital and multifaceted given with diverse culture, teachers' and students' digital literacy, social status and economic background [8]. Likewise, numerous changes as result to the fast-changing society, economic expansion and technological advancements shifted how people live. These changes create gaps between countries and continually strive economically to achieve a sustainable nation[2].

In achieving the SDGs, digital technology is also considered as a critical enabler by enhancing transparency, efficiency and inclusivity across sectors including health, economy, environment and education. The potential it holds in accelerating the achievement of SDG targets lies from enhancing education opportunities to making impacts to other SDGs accordingly [9]. Since technology is continuously revolutionizing in many fields, its capacity to deliver change is considered vital in the attainment of effective and sustainable means of development. However, the success of leveraging its role in the achievement of SDGs can be fueled by the newly created technologies and innovations that are boosted by collaboration and strengthened knowledge-sharing in the local and global context [10].

Digital technologies pave the way to address challenges and barriers of academic opportunities, ensuring the continuity of learning despite geographical, economic, social and health issues. Therefore, understanding the role of technology integration to address SDGs in education is crucial. Such insights can help educators and policymakers to determine its potential role, and ways in which it can be utilized to achieve the SDGs by 2030 [11].

Different digital learning platforms link abstract concepts and hands-on learning experiences through practical applications. Those technology makes personalized learning that provides students with opportunities to pursue the interest on the chosen career or specialization. [7].

Moreover, gamification is a technique that ensembles active learning while honing students' abilities to be critical thinkers and problem solvers through the help of affective engagement and discovery learning as gamification improves project-based learning. Also, gamification tends to resonate with students who are familiar with the mechanics and approach [12].

A comprehensive review demonstrated gamification's capacity to increase user engagement, motivation, and cooperation in various sustainability situations [13]. The study found that gamification promotes long-term actions in education, community projects, and organizational tactics.

Employing video instructional methods, it is revealed that students' consciousness of global issues is amplified through video storytelling and virtual reality [14]. These technologies develop empathy or attitudes and motivate learners to undertake sustainable actions by enabling them to see real-world challenges.

In relation to project learning, SDG themed projects considerably enhance awareness, critical thinking, and social as well as environmental activism among university learners [15]. Voucher[3] endorses this by demonstrating how primary pupils develop sustainability knowledge, cognition, and practice through technology-enabled projects such as sustainable cities design.

4 RESEARCH OBJECTIVES

This study aims to examine the relationship between the students' awareness on the SDGs and the local engagement in the community which affects by the globalization that contributes to the achievement of the United Nations Sustainable Development Goals (SDGs).

More specifically, it seeks to:

1) Segment students based on their KAP (Knowledge, Attitudes, and Practices) profiles.
2) Analyze the relationship between the students' knowledge, attitude and practices on the SDGs.
3) Evaluate the roles of technology integration in the achievement of the SDGs in terms of interactive learning, gamification, video-based learning and project-based learning.

[2]UN ECOSOC, 2008. https://press.un.org/en/2008/ecosoc6354.doc.htm

[3]Educational Service Contracting (ESC) Voucher Program /DepEd https://www.deped.gov.ph/wp-content/uploads/FY-2024-Major-Projects-Program-and-Activities-Beneficiaries.pdf

4) Analyze the relationship between the roles of technology integration and the students' KAP (Knowledge, Attitudes, and Practices) on the SDGs.
5) Develop a model that explains how different KAP (Knowledge, Attitudes, and Practices) segments influence the advancement of SDGs through technology integration.
6) Identify key patterns and gaps in students' technology-related practices that could impact the achievement of SDGs.
7) Recommend targeted strategies for curriculum development and technology initiatives that are aligned with the needs of different student segments.

5 METHODOLOGY

5.1 Research Design

This study employed a quantitative descriptive-correlational research design to examine the relationship between university students' knowledge, attitudes, and practices regarding the SDGs and their local engagements in the community. This research design allows for the systematic measurement and analysis of students' knowledge, attitudes, practices and the roles of technology integration to achieve SDGs.

5.2 Respondents of the Study

The respondents of the study are the university students enrolled in the Contemporary World Classes for the current academic year 2024-2025, with a total population of 430 students. A stratified random sampling technique was used to represent equal participation among different programs within the university. Using the Raosoft sampling, considering the 95% confidence level and 5% marginal error, a total of 205 samples were selected.

5.3 Data Gathering Instrument

The study utilized an adapted survey questionnaire divided into two parts, with established validity and reliability from prior research.

There were 2 parts to the questionnaire. Part I focused on the knowledge, attitude, and practice towards the Sustainable Development Goals dapted from a study [16] published in the Journal of Indonesia Sustainable Development Planning, while Part II focused on the technology integration and its roles in achieving SDGS. A 4-point Likert Scale was used in assessing the students' knowledge, attitude, and practices (KAP) in the role of technology integration.

5.4 Data Collection

Experts in the social science field and research have validated survey instruments to guarantee the suitability and relevance of each question. Thirty (30) students who were used in the pilot testing were not included in the main study. Using Cronbach's Alpha, the results were examined to evaluate the instrument consistency and dependability. Cronbach's Alpha value for the students' knowledge obtained an alpha value of 0.93; students' knowledge obtained an alpha value of 0.92 and students' practices obtained an alpha value of 0.80. For the sub-variables pertaining on the roles of technology obtained alpha value as follows – interactive learning, 0.89; video-based learning, 0.70; and in project-based learning, 0.86. the obtained alpha value from the conducted pilot testing signify that the research tool is valid and reliable which the data to be collected can assess the targeted parameters. After the validation phase, the survey questionnaires were distributed via online platforms. Prior to the distribution set of instructions were given to the participants.

5.5 Data Analysis

In this study, descriptive statistics were used to provide an analysis on the collected data from the survey responses. Through K-means cluster analysis, two distinct student clusters were segmented based on Knowledge, Attitudes, and Practices (KAP) towards the Sustainable Development Goals (SDGs). The researchers used the Pearson correlation coefficient to describe the strength and direction of a linear relationship between two continuous variables. The analysis of variance (ANOVA) was being utilized to identify the relationship of the variables. Multivariate Analysis of Variance (MANOVA) which is a statistical technique used to examine whether there are differences between segmented or clustered students on two or more dependent variables at the same time was also used. Structural equation modeling (SEM) analysis was used to provide compelling evidence for the significant role of Knowledge in shaping both Attitudes and Practices related to sustainable development goals (SDGs).

5.5 Ethical Considerations and Limitations

The study was carried out at a single academic institution, which may restrict the representativeness of the results to other Higher Education Institutions (HEIs), especially those operating with different cultural contexts, environment, or institutional profiles. Furthermore, there is a limited number of respondents as the institution is relatively new. It reduces the extent on which the result can be applied in other settings.

Moreover, this study relied heavily on quantitative methods of data collection and analysis. This may have limited depth of qualitative insights, specifically in capturing students' personal experiences and perceptions related to the affective component of the questionnaire. As such the exclusive dependence on quantitative data presents a methodological constraint on other aspects of interpreting and analyzing the data.

The study adhered to established ethical standards to ensure the protection and identity of all the participants. Before the data collection, participants were informed about the purpose study. It was clearly explained that participation was voluntary an in times of confusion, the participants have the right to withdraw at any time without consequences. The confidentiality and anonymity of the respondents were strictly maintained ensuring participants' identities were not recorded. The data collected was secured, stored and used solely for the purpose of the study. Additionally, the instrument used was carefully designed to be non-invasive and respectful of individual opinions and experiences. More importantly, ethical clearance was obtained from the ethics committee, affirming that the study complied with the established guidelines for research involving the participants.

Figure 1 shows the segments of the students based on their KAP (Knowledge, Attitudes, Practices) profiles. As gleaned from the figure, Cluster 1 (Moderately High KAP) are the students who have slightly above average scores in Knowledge (+0.59), Attitude (+0.59), and Practice (+0.48) about SDGs. This group (n = 129, 62.93%) exhibited moderately higher levels of knowledge, positive attitudes, and active practices related to the SDGs – better than average.

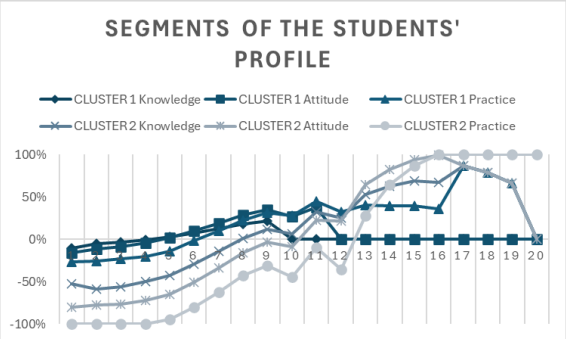


Figure 1: Segments of the students based on the KAP profile.

6 RESULTS AND DISCUSSION

Cluster 2 (Low KAP) are the students who have below average scores in Knowledge (-1.01), Attitude (-0.99), and Practice (-0.82) about SDGs. These segmented students are not aware, with negative attitude, and inactive toward SDGs. This group (n = 76, 37.07%) demonstrated lower levels of knowledge, less favorable attitudes, and fewer practices toward the SDGs.

The results suggest that a majority of students are relatively aware and engaged with SDG-related concepts and actions, while a notable minority requires additional support and intervention. The result supports the study of Filho, et. al. (2024) [6] which highlighted the comparison of the undergraduate students in Higher Education Institution (HEIs) to those who graduated already are more familiar in SDGs. In terms of students' knowledge and participation, it is strongly influenced by whether the university actively integrates the SDGs in their curriculum. The study also emphasized that regardless of the initiatives, students might still have differences in knowledge and practice depending on academic background and personal engagement.

However, although 62.93% of students in Cluster 1 exhibited positive KAP levels, the study of Baron, et. al. (2024) [17] suggests that many students might have surface-level awareness, but not fully aware of SDGs. This awareness does not guarantee deep understanding and actionable knowledge, as similarly reflected by the 37.07% of students in Cluster 2. Thus, it is recommended that educational institutions enhance strategies in achieving sustainability by 2030 by infusing these goals in their curriculum.

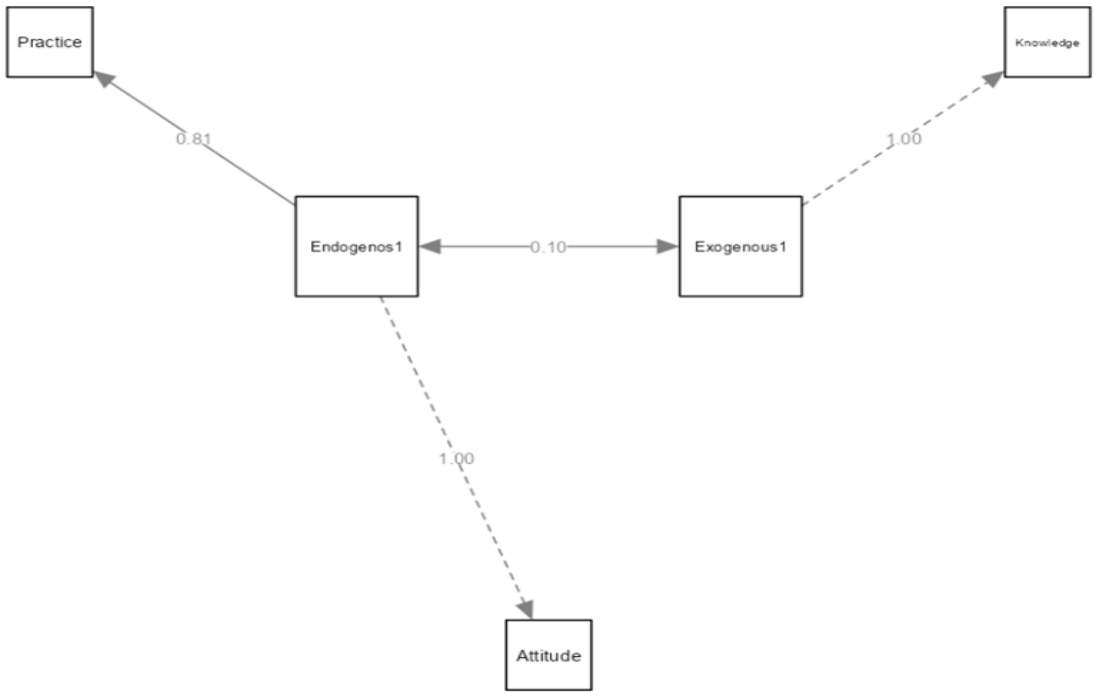


Figure 2: Relationship between KAP and the SDGs.

Figure 2 shows the relationship between Exogenous Latent Variable: Exogenous1 (measured by Knowledge) and the Endogenous Latent Variable: Endogenous1 (measured by Attitude and Practice). Attitude strongly measures Endogenous1 (β = 0.918) while practice moderately measures Endogenous1 (β = 0.634). Exogenous1 (Knowledge) is strongly positively correlated with Endogenous1 (Attitude and Practice), β = 0.757, highly significant.

With this data, the SEM model fits perfectly based on all indices. Knowledge (Exogenous1) is strongly associated with Attitude and Practice (Endogenous1). Both Attitude and Practice are good indicators of Endogenous1, but Attitude has a stronger contribution. The model is statistically sound and reliable.

The structural equation modeling (SEM) analysis indicated an excellent model fit, with all fit indices reaching ideal values (CFI = 1.000, TLI = 1.000, RMSEA = 0.000, SRMR = 0.000). The specified model identified Knowledge as an exogenous latent variable and Attitude and Practice as indicators of an endogenous latent construct. The path analysis revealed a strong and significant positive relationship between Knowledge and the latent endogenous variable (β = 0.757, p <.001). As gleaned in the model, among the parameters, Attitude obtained the highest standardized loading value of β = 0.918 while Practice obtained β = 0.634 which are both significant.

These data accepted the validity of the model used that Knowledge significantly affects the progress of Attitudes and Practices. Also, the data of the Structural Equation Modeling (SEM) analysis explain the positive role of Knowledge in honing the students' Attitudes and Practices in the achievement of the Sustainable Development Goals (SDGs). As demonstrated by the CFI, TLI, RMSEA and SRMR, the used model confirmed the interconnectedness among the latent variables. Students with high knowledge about SDGs most likely to have more positive attitudes towards sustainable habits and practices.

This finding aligns with the study of Sahaharuddin, et al. (2025) [18] showing a strong correlation in terms of students' knowledge, attitude and practice towards SDG. Students who have a higher level of knowledge most likely possess positive attitudes in SDGs. On the other hand, knowledge alone does not always guarantee positive practice or application making attitude as the mediating factor to attain better practice. In contrast with the result, the study of Afroz and Ilham (2020) [16] presented another perspective, indicating that knowledge and attitudes have a weak negative correlation compared to attitude and practice which

demonstrated positive correlation. The result suggests that the awareness through knowledge might be high, but the engagement is weak which disconnects knowledge and action.

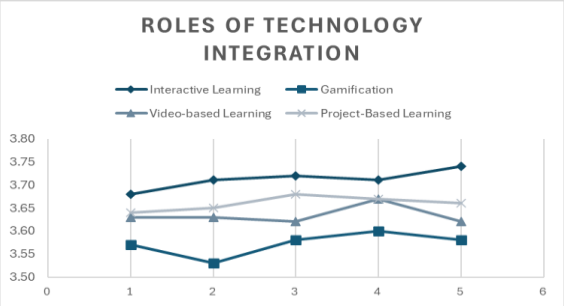


Figure 3: The roles of technology integration.

Figure 3 shows that among all the roles of technology integration, interactive learning consistently scores the highest which suggests that it is the most important due to its engaging and participatory nature that promotes active involvement. Likewise, project-based learning and video-based learning remain close in value reflecting how these two roles lead to overlapping perceptions of their importance. The overlap between video-based Learning and Project-based learning in the graph occurs because these two strategies are often used together in practice and it supports independent learning. It can also be explained that these two roles reflect natural integration and complementarity. Gamification, on the other hand, consistently has the lowest scores which indicate that while gamified elements can enhance motivation, they may not always be perceived as contributing significantly to deeper learning outcomes.

The result supported the study of Cadiz, et al. (2024) [19] which claims the role of technological integration in the educational paradigms to meet the demands of the Fourth Industrial Revolution. These includes the identified five key themes such as the interplay of technology with Education 4.0 and Industrial Revolution 4.0; the role of digital technology; shifts in educational philosophies; transformations in technology education; and the relationship between higher education, learners and technology. Through this, HEIs can promote academic excellence and resilience in the evolving landscape of education in achieving the SDGs through interactive learning set-up.

While gamification yields the lowest score among the four technological-related variables, the study by Navarro-Espinosa et al. (2022) [20] revealed how gamification can effectively boost student motivation and engagement in higher education, creating more interactive and impactful learning experiences if utilized meaningfully. By incorporating game-like elements, institutions can foster sustainable learning environments and promote the development of essential skills, making education more dynamic and student-centered.

However, the results for the other variables were aligned to the results of several studies. In terms of Video-based Learning, Torion and Bacio Jr. (2024) [21] through a developmental research method revealed that the content, instructional quality, technical design, and presentation, use of video lessons is highly acceptable proving their effectiveness as learning tools in computing education. Likewise, a study on the impact of Project-Based Learning (PBL) on students' awareness of SDG gained a positive result [15].

However, even though PBL can effectively increase knowledge in SDGs, it is important to strengthen this through strategies such as curriculum integration to ensure practical application to future endeavors.

Table 1 shows that all the Pearson correlation coefficients (r-values) are positive and statistically significant (p-value < 0.001, marked with *, **, ***) with the 95% Confidence Intervals (CI), indicating that there are strong positive relationships between the variables. The 95% Confidence Intervals (CI) provide additional insight into the range of correlation values, helping to understand the precision of the estimated correlation.

Knowledge is positively correlated with Attitude (r = 0.695), Practice (r = 0.480), Interactive Learning (r = 0.587), Gamification (r = 0.510), Video-Based Learning (r = 0.511), and Project-Based Learning (r = 0.576). The data explain that as students' knowledge of SDGs increases, their attitudes, practices, and engagement with different technology integration strategies (like interactive learning, gamification, and project-based learning) also increase. Attitude shows a strong positive correlation with Knowledge (r = 0.695), Practice (r = 0.582), Interactive Learning (r = 0.676), Gamification (r = 0.591), Video-Based Learning (r = 0.627), and Project-Based Learning (r = 0.662). it shows that students who have a positive attitude toward SDGs tend to show higher knowledge, better practices, and greater engagement with technology-based learning methods. Practice has moderate correlations with Knowledge (r = 0.480), Attitude (r = 0.582), and the technology integration methods. Specifically, Interactive Learning (r = 0.497), Gamification (r = 0.534), Video-Based Learning (r = 0.528), and

Project-Based Learning (r = 0.510). Also, there is a moderate relationship between students' sustainable practices and their knowledge and attitudes towards SDGs, as well as their involvement in technology-enhanced learning.

It can be gleaned in Table 1 that all technology integration methods (Interactive Learning, Gamification, Video-Based Learning, Project-Based Learning) show strong positive correlations with each other, with the highest correlation between Interactive Learning and Project-Based Learning (r = 0.800). Students who engage with one type of technology-based learning (e.g., interactive learning) are more likely to engage with others (e.g., project-based learning, gamification). All correlations have a p-value < 0.001, indicating that the relationships observed are highly statistically significant. This means the likelihood that these correlations happened by chance is very low.

Knowledge and Attitude are highly correlated with each other and the other components, indicating that better knowledge and more positive attitudes toward SDGs are associated with higher practices and engagement with technology-enhanced learning. Practice shows a moderate but significant correlation with Knowledge, Attitude, and the technology integration variables, suggesting that engaging with technology in the classroom helps improve students' sustainable practices. There is a strong relationship between all the technology-enhanced learning variables, implying that students who participate in one form of technology-based learning tend to engage in others as well. The correlation analysis reveals significant positive relationships between Knowledge, Attitude, Practice, and various technology integration variables (Interactive Learning, Gamification, Video-Based Learning, Project-Based Learning). All correlations are statistically significant with p-values less than 0.001, indicating that the relationships are not due to chance.

Figure 4 shows that the Exogenous1 (Technology Integration) has the following estimates for its indicators, Interactive Learning: Estimate = 1.000 (Reference variable), Gamification: Estimate = 1.098 (Strong positive association with Exogenous1), Video-based Learning: Estimate = 1.157, Project Based Learning: Estimate = 1.184. These estimates suggest that Project-Based Learning has the strongest contribution to the Exogenous1 latent variable, followed by Video-based Learning and Gamification.

The Endogenous1 (KAP-Knowledge, Attitude, Practice): Knowledge: Estimate = 1.000, Attitude: Estimate = 0.965 Practice: Estimate = 0.834. The Knowledge indicator is the most strongly associated with Endogenous1, followed by Attitude and Practice.

Table 1: The relationship of KAP Towards SDGs and Technology Integration

Variables	Attitude	Practice	Interactive Learning	Gamification	Video-based Learning	Project-based Learning
Knowledge	r =.695*** df = 203 p <.001	r =.480*** df = 203 p <.001	r =.587*** df = 203 p <.001	r =.510*** df = 203 p <.001	r =.511*** df = 203 p <.001	r =.576*** df = 203 p <.001
Attitude	—	r =.582*** df = 203 p <.001	r =.676*** df = 203 p <.001	r =.591*** df = 203 p <.001	r =.627*** df = 203 p <.001	r =.662*** df = 203 p <.001
Practice		—	r =.497*** df = 203 p <.001	r =.534*** df = 203 p <.001	r =.528*** df = 203 p <.001	r =.510*** df = 203 p <.001
Interactive Learning			—	r =.636*** df = 203 p <.001	r =.684*** df = 203 p <.001	r =.800*** df = 203 p <.001
Gamification				—	r =.690*** df = 203 p <.001	r =.701*** df = 203 p <.001
Video-based Learning					—	r =.796*** df = 203 p <.001
Legend: * p <.05, ** p <.01, *** p <.001						

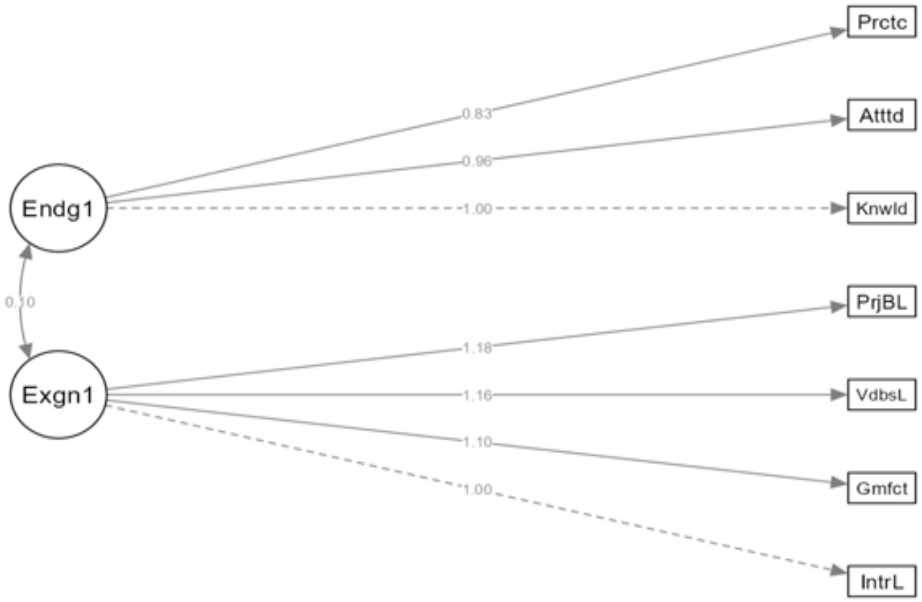


Figure 4: The relationship between the roles of technology integration and the students' KAP (Knowledge, Attitudes, and Practices) on the Sustainable Development Goals (SDGs) using the SEM Model.

The model fit is generally good, as indicated by the Comparative Fit Index (CFI), Tucker-Lewis Index (TLI), and Normed Fit Index (NFI) indices, which are all above 0.90. However, the Root Mean Square Error of Approximation (RMSEA) is slightly above 0.05, suggesting that there may be some room for improvement. As gleaned on the model, the Exogenous 1 (Technology Integration), it is clearly shown that the Exogenous 1 (Technology Integration) is significantly intertwined with its indicators with the highest positive association-project-based learning followed by the video-based learning and the gamification. Also, the KAP Model showed that Knowledge had the strongest indicator of the Endogenous1 latent variable. It was shown that there is a moderate relationship between Exogenous1 (technology Integration) and the Endogenous1 (KAP).

It was also shown that the Exogenous 1 (Technology Integration) has a positive impact on the Endogenous1 (KAP-Knowledge, Attitudes and Practices) with the project-based learning as the most significant component of the Exogenous1. The indices of the SEM model indicate a solid fit with the slight improvements to reduce the RMSEA.

The relationship between the technology integration and the knowledge, attitudes and practices is moderately significant signifying a good data. These findings noted the significant positive relation between technology integration specifically the project-based learning and the KAP dimensions. Additionally, the relationship between Technology Integration and KAP was moderate, implying that the use of technology, particularly in interactive and project-based learning environments, contributes positively to students' knowledge, attitudes, and practices. This study highlights the significance of technology integration into education context to enhance learning outcomes, but also suggests that further refinement of the model, particularly in terms of improving the RMSEA, could offer a more precise understanding of these relationships.

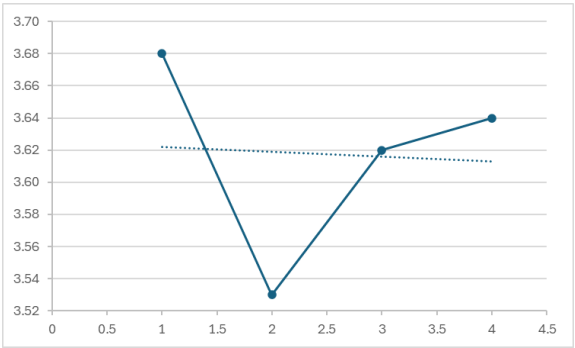


Figure 5: Key patterns and Gaps in students' technology-related practices towards SDGs.

Figure 5 reveals that interactive learning has the most important role while gamification specifically the indicator that states "using gamification to enhance understanding of specific SDGs"

consistently lags highlighting a potential gap in its educational impact. The clear dip in the line highlights this disparity. The moderate scores of video-based and project-based learning suggest that while useful, they do not reach the same level of engagement or learning depth perceived in interactive methods. This visual gap stresses the need to balance engagement with substance when integrating technology in education.

In contrast, while gamification has significant effect in learning, the study of Rodrigues et al. (2022) [22] revealed that gamification's impact follows the novelty effect or the initial interest of a person or excitement which subdue overtime as the newness wears off. This highlighted the importance for educators to reflect and be creative or innovative by considering how long the impact of the used gamification will last and how long does it will take to recover after noticeable reduction in benefits. The results align with the findings of Diaz and Estoque-Loñez (2024) [23] who conducted a study on gamification. Their study reviewed fifteen empirical studies published between 2018 and 2022, examining the impact of gamification across five moderator variables. It was also revealed that gamification meaningfully and significantly related to the student performance. However, analysis revealed that the five moderator variables did not exhibit statistically significant effects. The results of the research lead to believe that gamification is effective in academic courses at all levels in the Asian context.

7 CONCLUSIONS

The analysis revealed several key findings regarding students' awareness of SDGs and the role of technology integration in supporting knowledge, attitudes, and practice:

1) Most students segmented as Cluster 1 are relatively aware and engaged with SDG-related concepts and actions while a notable minority segmented as Cluster 2 requires additional support and intervention.
2) The results of the structural equation modeling (SEM) analysis provide compelling evidence for the significant role of Knowledge in shaping both Attitudes and Practices related to sustainable development goals (SDGs). The positive association between Knowledge and both Attitude ($\beta = 0.918$) and Practice ($\beta = 0.634$) suggests that individuals with higher knowledge about SDGs tend to exhibit more favorable attitudes and engage in more sustainable practices.
3) Among all the roles of technology integration, interactive learning consistently scores the highest which suggests that it is the most important due to its engaging and participatory nature that promotes active involvement.
4) There is a significant positive relationship between Knowledge, Attitude, Practice, and various technology integration variables (Interactive Learning, Gamification, Video-Based Learning, Project-Based Learning).
5) The SEM model suggests that Technology Integration (Exogenous1) has a positive impact on KAP (Knowledge, Attitude, and Practice), with Project-Based Learning being the most influential component of technology integration.
6) Interactive learning has the most important role while gamification, specifically the indicator that states consistently lags highlighting a potential gap in its educational impact.

8 RECOMMENDATIONS

It is recommended that the use of technology, particularly in interactive and project-based learning environments, contributes positively to students' knowledge, attitudes, and practices. This study highlights the significance of technology integration in the classroom settings to enhance learning outcomes but also suggests that further refinement of the model.

To address the gaps of different clusters, teachers can use strategic intervention framework for curriculum instruction based on Vygotsky's Principles. This will provide support enrichment, guided by sociocultural learning theory. For Lower Cluster the instructional focus is on the foundational understanding of SDGs and Globalization. Educators can approach this through scaffolded learning using ZPD. Interactive digital tools such as videos and gamified modules can be utilized with structured prompts for modeling and guided practice. While those on the higher cluster can challenge their critical thinking through capstone projects where they can do policy analysis or digital advocacy campaign. This approach is based on social constructivism learning theory where learning as a social process includes peer collaboration a culturally relevant tools to support deeper understanding).

Since the study was conducted in a Philippine context, it is recommended that CHED and other

HEIs institutionalize the integration of SDG-based performance tasks within the general course specifically The Contemporary World. This may include revision of syllabi to include outcomes-based projects aligned with SDGs, training programs for faculty and administrators on sustainability education and the adoption of digital pedagogical tools to develop greater global awareness and civic responsibility.

Moreover, consistent implementation of monitoring and evaluating mechanisms are necessary to assess effectiveness of SDG integration in course delivery. This will ensure a positive impact on students' knowledge, attitudes, and practices regarding sustainable development.

For teachers, it is highly recommended that they to continue Professional Development Initiatives (PDIs) through In-Service Trainings (INSETs), particularly on the unique goals and content of The Contemporary World course. These trainings will support teachers in enhancing learning materials and digital resources aligned with SDG-related themes. Integration of interactive learning tools, gamification techniques, video-based instruction, and project-based learning are effective ways to enhance students' engagement and global awareness.

Additionally, such training can help educators assess how they can effectively utilize these technologies in key topics of TCW emphasizing related SDGs. It will enable them to deliver more contextualized, meaningful and socially responsive instruction leading to students' development of actionable solution to global issues. Consequently, these trainings can serve as learning avenues for teachers to enrich their own understanding of SDGs which is essential for the genuine, informed, and meaningful delivery of lessons. It is a holistic approach that ensures educators are not only equipped with the right tools but are also well-grounded in the principles and purpose of sustainable development.

Finally, further studies are encouraged to replicate this research across different educational contexts and academic levels to validate the findings and explore additional dimensions of effective educational interventions. Replication may be extended in the context of Environmental Science, English language and Literature and other subjects where SDGs are highly relevant. This encourages interdisciplinary approaches from various perspectives that can enrich pedagogy promoting critical thinking and problem solving, and global awareness. Replication and expansion of the study will help ensure broader applicability and continuous improvement of education in line with both national standards and global commitments.

This study primarily focused on student's level of awareness and understanding of SDGs. Future research may shift the lens towards educators—assessing the depth of teachers' understanding of SDGs and their readiness to deliver meaningful lessons aligned with the global goals. Investigating teachers' pedagogical preparedness could offer insights to capacity-building needs and contribute to the improvement of current curriculum.

Moreover, while the study highlights the positive attitudes of students toward technology integration in achieving SDG-related learning, future studies may also look at the practical challenge of implementing such integration. In the context of the Philippines, questions of technological readiness, access to facilities, availability of possible educational tools must be look at. Investigating these barriers may inspire initiatives of meaningful collaborations between HEIs, policymakers, and educational technology providers to develop sustainable, inclusive digital learning ecosystems.

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IPFS-Enabled Blockchain Framework for Fair Payment Systems

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Keywords: Fair Payment Systems; Smart Contracts; IPFS (Interplanetary File System); Off-Chain Storage; Decentralized Storage.

Abstract: Blockchain-based fair payment systems have gained considerable attention due to their potential to facilitate transparent, secure, and automated transactions. However, managing large-scale digital assets directly on-chain is impractical due to blockchain scalability constraints, high transaction fees, and limited storage capacities. Existing solutions often employ centralized cloud-based storage services for off-chain data, introducing trust dependencies, censorship risks, and undermining core decentralization objectives. This paper presents a preliminary exploration into integrating the InterPlanetary File System (IPFS) a decentralized, peer-to-peer storage protocol with blockchain smart contracts to enable fully decentralized off-chain storage for fair payment systems. We propose a conceptual model leveraging IPFS to ensure verifiable data delivery, automated dispute resolution, and trustless payment settlements. Preliminary qualitative analysis and comparative evaluations highlight substantial improvements in decentralization, transparency, and resilience compared to traditional cloud-based approaches. Our results demonstrate the feasibility and potential advantages of employing IPFS in blockchain payment frameworks, paving the way for truly decentralized digital asset management and exchange systems.

1 INTRODUCTION

Blockchain technology has profoundly reshaped digital transactions, enabling trustless, transparent, and secure payment processes without relying on central authorities or intermediaries [1], [2]. Decentralized payment systems, leveraging blockchain smart contracts, have gained significant attention for their potential to automate financial exchanges, eliminate fraud, and enhance transparency in various digital economies. However, one persistent challenge in realizing truly decentralized blockchain-based applications (dApps) is efficiently managing the storage and distribution of substantial digital assets, as direct on-chain storage remains impractical due to inherent scalability constraints, limited block sizes, and high transaction costs [3], [4].

To work around on-chain limits, many "decentralized" payment systems quietly park their off-chain data in a regular cloud bucket think S3 or GCS while the chain stores only a pointer or hash [5]. It's hard to argue with the convenience: elastic storage, global CDNs, familiar APIs, and a bill that (usually) makes finance happy. But the trade-offs are familiar, too. A single account suspension, a region hiccup, or an ACL misconfiguration can take data offline. Takedown requests and policy changes can nudge toward de-facto censorship. And unless versioning and audit trails are enforced and actually monitored subtle tampering may slip by [6], [7]. All of that sits uneasily with what blockchains were supposed to buy us. These central points of control and failure appear to undercut resilience, fairness, and the neutrality we expect from a decentralized payment system. The approach works, yes – but it bends the architecture back toward the very trust assumptions it set out to avoid.

Decentralized off-chain storage most visibly IPFS has been gaining traction as an alternative to parking data in a single cloud account. IPFS runs over a peer-to-peer network and uses content addressing: every file is referenced by a CID (essentially the hash of its bytes), so if the content changes, the CID changes too. That setup makes tampering easy to spot and, in many cases, hard to get away with; it also appears to blunt

platform-level takedowns since copies can live on independent nodes rather than one provider [8], [9]. It isn't magic, though. Availability depends on pinning and who's actually hosting the data – teams often pin to a couple of providers and keep a local node as a backstop. Even with those caveats, recent work has used IPFS for decentralized sharing, archival records, and computation pipelines, reporting advantages over traditional cloud models in integrity checks and resilience to outages [10], [11]. However, few studies systematically integrate IPFS with blockchain-based payment protocols, particularly regarding automated payment settlement and dispute resolution, thus leaving critical gaps unresolved.

Motivated by these considerations, this paper presents a novel approach that integrates IPFS as decentralized off-chain storage with blockchain-based smart contracts to establish an end-to-end fair payment system. The proposed framework aims to ensure trustless verification, transparent settlement, and automated dispute management while eliminating reliance on third-party storage providers. Specifically, this research provides the following key contributions:

- A detailed conceptual model demonstrating how IPFS can be integrated seamlessly with blockchain-based payment mechanisms.
- Qualitative analysis highlighting the advantages, feasibility, and potential limitations of the proposed decentralized storage approach compared to traditional cloud-based solutions.
- A preliminary scenario illustrating dispute resolution processes within the IPFS-based fair payment system, supported by conceptual diagrams and comparative tables.

The remainder of the paper is structured as follows: Section II defines the problem context and motivation, Section III reviews related literature, Section IV describes the proposed architecture and methodology, Section V presents preliminary findings and analysis, and Section VI concludes with future directions.

2 PROBLEM DEFINITION

Blockchain-based payment systems have attracted considerable attention due to their potential to enable transparent, secure, and automated financial transactions without reliance on central intermediaries [1], [2]. Nevertheless, decentralized applications (dApps), particularly those designed for fair payment and digital asset management, frequently require storing and managing large-scale or complex data. Directly storing such data on-chain is impractical due to blockchain limitations such as restricted block sizes, limited scalability, and prohibitive transaction costs [3], [12]. As a result, existing decentralized payment systems typically utilize centralized cloud services for off-chain storage to alleviate these constraints and reduce blockchain-related expenses as depicted in Figure 1 [5] [13].

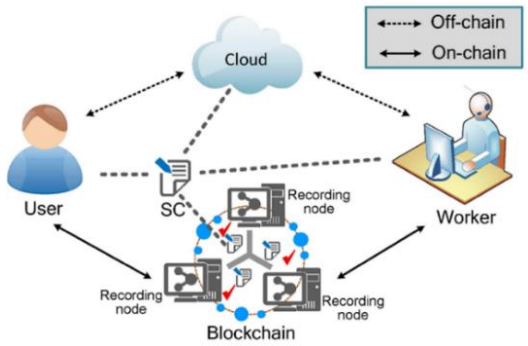


Figure 1: Decentralized payment systems relying on centralized cloud services for off-chain storage.

Cloud services scale nicely and are easy to use, but leaning on a single provider sits awkwardly with the goals of decentralization, transparency, and minimizing trust [14]. A suspended account, a misconfigured bucket policy, or a regional outage can knock data offline; takedown requests and shifting terms can amount to soft censorship [15]. You also inherit new trust anchors provider admins, access keys, internal ACLs the very stuff blockchains try to avoid. And while clouds promise high durability, they don't, by default, give you content-addressed proofs or independently reproducible audit trails; long-term integrity, availability, and verifiability become policy claims rather than cryptographic facts. That gap complicates disputes and appears to leave fair-payment flows exposed to manipulation missing files, swapped blobs, or back-dated uploads are hard to rebut without external evidence [16].

There's still a stubborn gap: an off-chain storage layer that preserves the same decentralization, censorship resistance, and minimal trust that blockchains promise on-chain. To chip away at that gap, we explore wiring IPFS a decentralized, peer-to-peer, content-addressed protocol directly into smart contracts [17], [18]. The idea is simple enough. Let the chain commit to CIDs while the actual bytes live off-chain. Verification then boils down to fetching the content for that CID and checking a signature, which

appears to give a practical, scalable, and easily verifiable path for settling payments without leaning on a single provider. Two caveats are worth flagging. Availability hinges on pinning and replication policies, and access control usually comes from encryption and key management rather than IPFS itself. Even with those reservations, the approach keeps the trust budget small and the system closer to the decentralization we set out to maintain.

3 RELATED WORK

Blockchain-based fair-payment schemes have become a go-to way to keep exchanges transparent and automated without leaning on a trusted middleman. The proposals cover a lot of ground: payment atomicity via conditional transfers or HTLC-style locks, stronger security with verifiable proofs, and fee cuts through batching or off-chain channels. A representative example is Zhang et al. [16]. Their protocol made the payment flow harder to break and, on paper, more dependable. Still, the design parked outputs in a centralized cloud bucket (think S3 or GCS) while the chain stored only references. That choice is understandable it's cheap and widely supported but it also nudges the system back toward a single provider and, by extension, appears to dilute the decentralization the blockchain layer is supposed to guarantee.

To sidestep the chain's storage ceiling, a lot of recent work parks off-chain data in regular cloud services – think S3 buckets or GCS blobs while the blockchain keeps only a pointer or hash [16], [19]. It's convenient and cheap, sure, but it appears to smuggle trust back in: an account suspension, a regional outage, or a sloppy bucket policy can take data offline; takedown requests can edge into soft censorship; and "integrity" often boils down to provider logs rather than cryptographic facts [18]. These cracks suggest we still need to look harder at decentralized, durable off-chain storage that fits blockchain assumptions systems where availability comes from replication, integrity comes from content addressing, and long-term verifiability doesn't hinge on a single company's dashboard.

Recent works have explored decentralized storage technologies such as the IPFS and Swarm to mitigate these challenges. Kumar et al. [4] presented an in-depth analysis of IPFS and Swarm, highlighting their compatibility with blockchain systems, especially emphasizing immutability and secure storage. Similarly, Benisi et al. [17] conducted a comparative assessment of IPFS and Swarm, emphasizing blockchain interoperability and the ability to guarantee data integrity in decentralized contexts.

Researchers have started leaning on decentralized storage mainly IPFS and, in some settings, Swarm to get around the obvious limits of parking data with a single provider. Kumar et al. [4] take a close look at both systems and argue they line up well with blockchain assumptions: content addressing helps you spot tampering, and data can live on multiple nodes rather than one vendor. Benisi et al. [17] offer a side-by-side comparison and come to a similar place, stressing interoperability with on-chain logic and the ability to verify that what you fetched is exactly what was written. That said, neither system is plug-and-play perfection. Availability still depends on who pins or incentivizes storage, and real-world latency can wobble with network churn. Even so, these studies appear to suggest that IPFS and Swarm are a better fit for decentralized workflows than a lone cloud bucket, especially when integrity and auditability matter.

Casino et al. [7] take a hard look at what "immutability" really buys you in decentralized storage and where it can bite. Freezing content by hash doesn't stop abuse; it can, in some cases, make takedowns messy. Once a harmful CID circulates, anyone can repin it, gateways may block inconsistently, and legal accountability gets murky. The authors highlight issues like malicious content dissemination, "poisoned" hashes used for harassment or denial-of-service, and the awkward linkability of CIDs to sensitive material. They also sketch practical mitigations: encrypt data client-side and manage keys off-chain; apply clear pinning policies; maintain gateway deny-lists with transparent audit logs; and design incentives that discourage hosting flagged content on IPFS-style networks. The bigger lesson appears to be that pairing decentralized storage with blockchains doesn't make safety a given you still need to engineer for abuse cases, compliance, and the tension between permanence and the need to remove harmful material.

Moreover, not all next-generation peer-to-peer data networks have embraced blockchain integration, due to concerns such as scalability and latency. Naik and Keshavamurthy [20] provided a general review of modern peer-to-peer (P2P) networks, analyzing the evolution of classical systems (e.g., BitTorrent, Chord) and newer models, with particular attention to their performance characteristics under node churn conditions. Notably, their classification categorizes IPFS as a classic P2P network. However, other recent perspectives suggest IPFS and similar technologies have significantly evolved, incorporating incentive

mechanisms and decentralized data management techniques that extend beyond traditional P2P models [9].

In terms of incentive mechanisms specifically designed for decentralized storage and delivery, Tit-for-Token (2023) presented peer incentivization protocols for IPFS-based systems, introducing economic models to foster resource sharing and fair compensation among peers [11]. Similarly, FileInsurer (2022) proposed mechanisms layered atop IPFS to enhance reliability through economic guarantees and deposit-based compensation models for data availability [21].

Despite the breadth of existing work, comprehensive solutions integrating decentralized off-chain storage with automated, blockchain-based fair payment remain limited. Few studies explicitly tackle challenges around dispute resolution, verification mechanisms, and persistent data availability when employing decentralized storage like IPFS. Thus, a gap remains in systematically combining these critical elements to form robust, decentralized payment systems.

We tackle the gap with a single, end-to-end path: wire IPFS directly into smart contracts so the chain commits to CIDs while the bytes live off-chain. That way, anyone can check what was stored (and when), payments settle under rules you can actually audit, and disputes run as code timeouts, bonds, compact proofs instead of going through a help desk. The aim is straightforward: keep trust out of the critical path, scale with rising job counts, and stay resilient when parts of the network wobble. It won't solve everything pinning policies and key management still matter but this unified approach appears to move fair-payment systems closer to the decentralization they promise, with verifiable storage, transparent settlement, and automated dispute handling that's practical in the real world.

4 IPFS AS OFF-CHAIN STORAGE

Much of the recent literature OBFP [13] and EFP [5] are typical keeps the bytes in a cloud bucket (think S3 or GCS) and writes only a hash or pointer to the chain to dodge storage fees. Pragmatic? Absolutely. It scales, ops teams know how to run it, and the bill is predictable. But the fit with blockchain's goals is shaky. Handing availability to a single provider quietly brings back a trusted third party: account suspensions, region outages, or an ACL slip can make data vanish, and takedown requests can act like soft censorship. Integrity, too, becomes a matter of provider logs and policies rather than end-to-end cryptographic proofs. That appears to undercut the very properties these payment systems claim to prioritize trustlessness, transparency, and resilience. None of this means clouds are "wrong" in every case; a hybrid setup (e.g., dual-cloud storage with periodic on-chain anchoring) may ease operations. Still, for fair-payment designs that aim to be genuinely decentralized, reliance on centralized infrastructure looks like a step back, not forward.

To tackle this limitation, we use IPFS as the off-chain storage layer, following the direction of Rani et al. [22], and Ma et al. [23]. The goal is straightforward: keep storage trustless and hard to censor while still scaling to real job sizes. With content addressing, the chain commits to a CID and the bytes live off-chain; if the file changes by even a single bit, the CID flips, which makes tampering obvious. Practically, this appears to cut our reliance on any single provider and helps with availability when multiple parties pin the same data (e.g., worker, client, and a small pinning service). It also shifts weight off the blockchain CIDs and small receipts on-chain, large artifacts on the P2P network which is likely to lower fees and keep state growth in check. Cloud buckets (S3/GCS) can be faster in some regions and are undeniably convenient, but they reintroduce a trust anchor we're trying to avoid. There are a few knobs to get right. IPFS doesn't do access control by itself, so sensitive outputs are typically encrypted client-side and keys managed off-chain. Pinning and replication policies matter, too; without them, availability can drift. Even with those caveats, replacing centralized off-chain storage with IPFS strengthens resilience and censorship resistance, and by distributing data across peers improves scalability and cost efficiency without bloating the chain.

The contribution of integrating IPFS into decentralized payment systems is a principled model for off-chain data management that advances trustlessness, transparency, and system autonomy. Conventional models often handle only the payment process on-chain while depending on centralized or semi-centralized repositories for off-chain data, introducing single points of failure, potential censorship, and weaker integrity guarantees. In the proposed design, IPFS serves as the off-chain storage layer that complements smart contracts managing fair payments. When a provider generates digital content or service outputs, the data are uploaded to IPFS, which fragments and distributes them across the peer-to-peer network. IPFS assigns a unique content hash (CID) that acts as an immutable, verifiable identifier; the provider then submits this CID to an on-chain

smart contract. The client can independently retrieve and verify the content from IPFS, ensuring it has not been altered. Figure 2 illustrates data availability in IPFS; reliable access depends on file pinning by one or more network nodes. Overall, the proposed approach not only mitigates the weaknesses of traditional off-chain storage models but also enhances the reliability, security, and efficiency of decentralized payment systems for outsourced service providers.

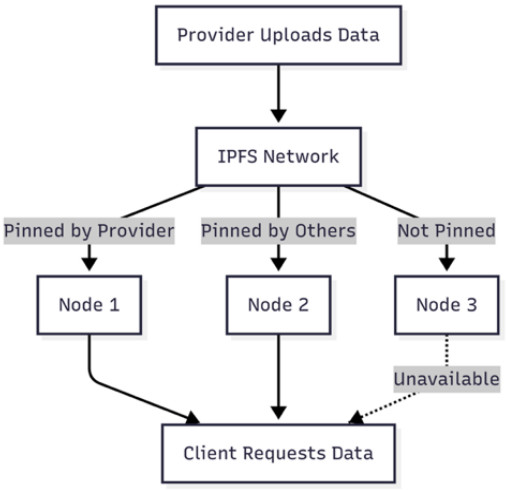


Figure 2: Illustration of data availability in IPFS that upload by service provider.

5 RESULTS AND DISCUSSION

This study presents a preliminary exploration of integrating IPFS as an off-chain storage solution within decentralized fair payment systems. Given the conceptual and prototype nature of the work, the results focus on the qualitative assessment of system behavior, feasibility, and anticipated advantages over traditional cloud-based approaches.

5.1 Feasibility and System Behavior

Through a prototype implementation and scenario analysis, the proposed model demonstrates several critical improvements. By leveraging the content-addressed architecture of IPFS, the system ensures data integrity and tamper-evidence without the need for trusted third parties. In the illustrative scenario of digital asset exchange, the provider uploads content to IPFS and submits the resulting hash to a blockchain smart contract. The client retrieves the file directly from IPFS using the hash, verifies its authenticity, and only then triggers payment release through the contract. This workflow depicted in Figure 3 confirms the model's capacity to automate fair settlement and transparent data verification.

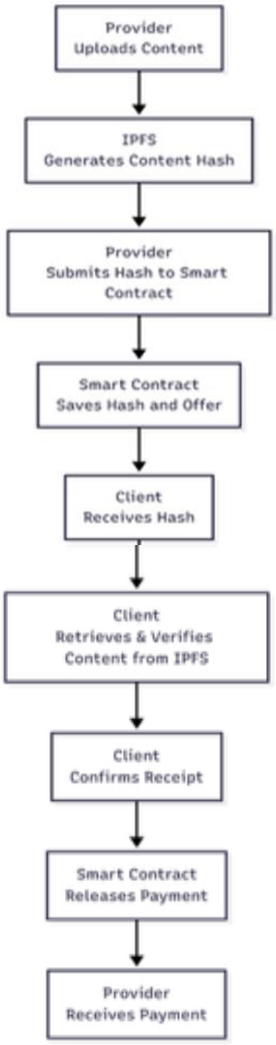


Figure 3: Automated fair settlement and transparent data verification workflow using IPFS and blockchain smart contracts.

5.2 Comparative Analysis

A qualitative comparison with conventional cloud-based off-chain storage models is presented in Table 1. The analysis highlights that, unlike centralized solutions, the IPFS-based model eliminates single points of failure and enhances censorship resistance. Furthermore, payment settlement and content verification are entirely automated and transparent via the smart contract,

significantly reducing operational risks. However, challenges remain regarding persistent data availability on IPFS, which depends on effective pinning and incentivization strategies. Retrieval latency was also identified as a variable factor, suggesting the need for further optimization in production-scale deployments.

Table 1: A qualitative comparison with conventional cloud-based off-chain storage models is presented and IPFS-Based Model.

Feature/Aspect	IPFS-Based Model (Proposed)	Cloud-Based Off-Chain Storage
Decentralization	Fully decentralized, peer-to-peer	Centralized (single/multi-cloud)
Data Integrity	Guaranteed by content hash (immutable)	Depends on provider
Payment Settlement	Automated via smart contract, trustless	Relies on third party logic
Censorship Resistance	High (difficult to remove data)	Low (provider can censor/delete)
Scalability	High, distributed across many nodes	Limited by provider infrastructure
Storage Cost	Minimal on-chain cost, pay for pinning	Pay-per-use or subscription
Data Availability	Requires persistent pinning/incentives	Guaranteed by provider SLAs
Transparency/Auditability	Fully transparent on blockchain	Limited to provider's reporting

5.3 Conceptual Findings

The conceptual results indicate that the integration of IPFS addresses key limitations of previous architectures. Specifically, the system:

- Reduces reliance on centralized infrastructure and trusted intermediaries.
- Guarantees data authenticity through content-addressed storage.
- Supports automated, trustless payment and dispute resolution.
- Provides robust transparency and auditability for all transactions.

5.4 Dispute Scenarios

The proposed IPFS-based fair payment model anticipates several principal dispute scenarios and incorporates dedicated resolution mechanisms to address each case, as detailed in Table 1. For instance, if data is not accessible on IPFS, the smart contract is designed to withhold payment and automatically trigger a refund or invoke timeout logic to protect the client. In cases where the content hash does not match the expected data, payment is withheld, and the client may explicitly reject the transaction or initiate a dispute process [18]. The system also addresses scenarios where a user falsely claims non-delivery by requiring explicit confirmation of receipt, with provisions for auditor intervention when necessary (Table 2), [24]. Additionally, slow or intermittent data retrieval is managed through timeout policies, allowing users to retry or abort the transaction as appropriate. Figure 4 show Dispute resolution process Payment is only released upon client confirmation of data retrieval, with timeouts and optional auditor intervention for unresolved cases. Finally, any attempt by the provider to submit a fake or malicious hash is counteracted by robust content hash verification within the contract, ensuring transparency and auditability using the algorithm shown in Figure 5. Collectively, these mechanisms provide an automated, fair, and trustless approach to dispute resolution, significantly enhancing the security and reliability of the decentralized payment framework.

Table 2: Common dispute scenarios and resolution mechanisms in the proposed IPFS-based fair payment model [18], [24].

Dispute Scenario	Model's Resolution Mechanism
Data not accessible on IPFS	No payment released; refund or timeout logic triggers
Content hash does not match expected data	Payment withheld; client can reject or trigger dispute
User falsely claims non-delivery	Requires explicit confirmation; possible auditor check
Data retrieval is slow or intermittent	Timeout policy; user may retry or abort transaction
Provider submits fake or malicious hash	Content hash verification prevents payment; transparency for auditing

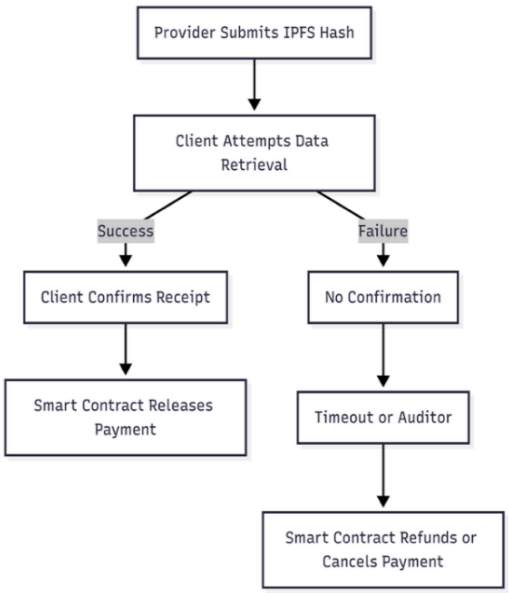


Figure 4: Workflow of dispute resolution process in the IPFS-based fair payment model.

```
Algorithm 1: Dispute Resolution in IPFS-
Based Fair Payment System

Input:
    ipfs_hash      // Content hash provided
by Provider
    timeout        // Maximum time for client
confirmation

1:  Provider submits ipfs_hash and initiates
payment via SmartContract
2:  Client attempts to retrieve and verify
data from IPFS using ipfs_hash

3:  if Client confirms successful retrieval
and verification before timeout then
4:      SmartContract releases payment to
Provider
5:  else
6:      if Auditor or Oracle is available
then
7:          Auditor checks data availability
on IPFS using ipfs_hash
8:          if Auditor confirms data is
available then
9:              SmartContract releases
payment to Provider
10:         else
11:             SmartContract refunds
payment to Client
12:         end if
13:     else
14:         SmartContract refunds payment to
Client after timeout
15:     end if
16: end if

17: SmartContract logs dispute and
resolution status on-chain
```

Figure 5: Pseudocode Representation of the Dispute Resolution Mechanism in the Proposed IPFS-Based Model.

We deployed a minimal escrow contract on Ethereum Sepolia and integrated it with IPFS for off-chain asset addressing. Using the CID QmPtUE…K44j, contract deployment consumed 978,042 gas (5.57 s), while the createDeal and confirmAndPay functions required 186,418 gas (10.85 s) and 61,843 gas (11.51 s), respectively. Complementary local IPFS measurements for ~1 MB assets showed sub-0.03 s upload and ~0.005 s retrieval times with SHA-256 verification. These results, summarized in Table 3, demonstrate efficient content-addressed storage and verifiable retrieval, supporting the feasibility of automating fair settlement conditioned on IPFS-based data verification, with on-chain costs concentrated in the initial deployment and escrow creation steps.

Table 3: Experimental results of escrow contract deployment and IPFS integration.

Operation	Resource/Asset	Gas Used	Time (s)
Contract Deployment	Escrow contract on Sepolia	978,042	5.57
CreateDeal	CID QmPtUE…K44j	186,418	10.85
ConfirmAndPay	CID QmPtUE…K44j	61,843	11.51
IPFS Upload	~1 MB asset	–	0.03
IPFS Retrieval	~1 MB asset	–	0.005

Figure 6. End-to-end prototype: (1) client uploads asset to IPFS and obtains CID; (2) escrow smart contract records CID and funds; (3) client verifies asset off-chain; (4) on successful verification, confirmAndPay releases payment; otherwise, a dispute/timeout path halts payout.

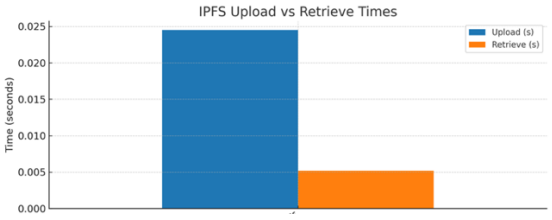


Figure 6: End-to-end prototype of upload and retrieve times.

Nevertheless, it is acknowledged that practical deployment will require additional mechanisms to ensure reliable long-term storage and efficient access, particularly for large or highly dynamic datasets. In summary, these findings support the conclusion that integrating IPFS with blockchain-based payment logic is a promising pathway for building scalable,

transparent, and fully decentralized fair payment systems. Future work will focus on quantitative performance benchmarking, incentive designs for storage reliability, and broader evaluation across diverse application scenarios.

6 CONCLUSIONS

This paper has presented a preliminary exploration of integrating the IPFS as a decentralized off-chain storage solution within blockchain-based fair payment systems. By addressing the limitations of centralized cloud storage, the proposed model leverages IPFS's content-addressed, peer-to-peer architecture to enhance data integrity, transparency, and censorship resistance. The integration of blockchain smart contracts with IPFS enables automated, trustless settlement and robust dispute resolution without reliance on third-party intermediaries. Qualitative analysis and scenario-based evaluation demonstrate that the model effectively mitigates common dispute scenarios and delivers substantial improvements in decentralization and security compared to conventional approaches. The study demonstrates the important and effective role of IPFS as off-chain storage approach in scalable the reach of blockchain applications to make them fully decentralized and trustless. Future work will focus on quantitative performance evaluation, large-scale prototype deployment, and the development of advanced incentive and persistence strategies to further strengthen reliability and practical applicability in real-world decentralized payment systems.

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Intrusion Detection in Smart Grids by Collective Learning Algorithm and Particle Swarm Optimization Algorithm

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Keywords: Smart Power Grid, Intrusion Detection, AdaBoost Algorithm, Particle Optimization Algorithm.

Abstract: In recent years, cyber-attacks targeting the physical infrastructure of modern power systems have significantly increased, posing serious risks to society and critical services. This study investigates intrusion detection in smart grids using a hybrid approach based on Particle Swarm Optimization (PSO) and the AdaBoost ensemble classifier. To enhance detection performance, data preprocessing techniques, including handling missing values and normalization, were applied. Subsequently, PSO was utilized for feature selection, reducing the original feature set from 40 to 30 optimal attributes. These selected features were then used as input to the AdaBoost classifier. The ensemble learning mechanism of AdaBoost combines multiple weak learners to improve classification reliability by focusing on misclassified instances and aggregating their outputs. This approach enhances detection capability compared to individual classifiers. Experimental results demonstrate that the proposed method achieves an accuracy of 92.9% on the test dataset, outperforming the baseline method by approximately 3%, which confirms the effectiveness of combining feature optimization with ensemble learning for smart grid intrusion detection.

1 INTRODUCTION

Smart grids represent a cyber-physical infrastructure in which communication networks are tightly integrated with physical power systems to enable efficient monitoring, control, and energy distribution [1], [2]. While this integration enhances operational efficiency, it also increases exposure to cyber-attacks that may result in severe physical, economic, and social consequences [3]. Unlike conventional communication networks, cyber intrusions in smart grids can directly affect power availability, system stability, and public safety [4].

Traditional security mechanisms such as firewalls, encryption, and authentication play an essential role in protecting communication infrastructures; however, they are insufficient to address sophisticated and previously unknown cyber threats [5], [6]. Consequently, Intrusion Detection Systems (IDSs) have become a critical component of smart grid security architectures, aiming to monitor system behavior and identify malicious activities that bypass preventive defenses [7], [8].

Despite their importance, the effectiveness of IDSs in smart grid environments is often limited by high-dimensional data, redundant features, and increased false alarm rates, which reduce detection reliability in real-world operational settings [9], [10]. To overcome these limitations, several detection paradigms have been proposed, including signature-based, anomaly-based, and description-based intrusion detection methods that focus on modeling normal system behavior [11], [12], [13].

In recent years, ensemble learning techniques have attracted increasing attention due to their ability to improve classification robustness by combining multiple weak learners [17], [18]. Among these techniques, AdaBoost has demonstrated effectiveness in reducing classification errors and variance. Nevertheless, the performance of ensemble classifiers remains highly dependent on feature quality and dimensionality, making feature selection

a critical step in intrusion detection systems [16], [19].

To address these challenges, this study investigates a hybrid intrusion detection approach that integrates Particle Swarm Optimization (PSO) for feature selection with the AdaBoost ensemble classifier [16], [20]. PSO is employed to select a reduced and informative subset of features, which is then used as input to the AdaBoost classifier to enhance detection accuracy while reducing false alarms. The effectiveness of the proposed approach is evaluated using the NSL-KDD benchmark dataset.

2 CONTRIBUTIONS OF THIS STUDY

The main contributions of this study can be summarized as follows:

- This study proposes a hybrid intrusion detection framework for smart grid environments by integrating Particle Swarm Optimization (PSO) for feature selection with the AdaBoost ensemble classifier.
- The proposed approach demonstrates that reducing the feature space prior to classification improves intrusion detection accuracy and reduces false alarm rates.
- An experimental evaluation is conducted using the NSL-KDD benchmark dataset, providing insight into the effectiveness and limitations of optimization-based ensemble learning for smart grid intrusion detection.

3 RELATED WORKS

Previous studies explored signature-based IDSs, which are effective for known attacks but limited in detecting unknown threats [13], [25]. Anomaly-based IDSs have been developed to be capable of detecting novel intrusions but are prone to high false alarms [12], [22]. Recent advancements introduced description-based IDSs to model system behaviors in detail [15].

In smart grids, IDSs have been classified into Host-based (HIDS), Network-based (NIDS), and Distributed architectures [14], [27]. Studies employing machine learning and optimization techniques, including neural networks, decision trees, and whale optimization algorithms, highlight the promise of hybrid approaches [28], [18], [19]. However, limitations remain in scalability, accuracy, and adaptability [29], [30], [31].

In the last few years, cyber-attacks on the physical infrastructure of smart electricity systems have increased [3], [20]. If such attacks are carried out successfully, they can cause many problems in people's lives. The prevalence of such attacks has raised concerns about the security of sensitive infrastructure [9], [10]. Therefore, despite these attacks, the use of intrusion detection in smart electrical systems has become necessary [7], [8]. If intrusion detection is performed in a network using more than one method, it will detect new attacks and reduce the rate of incorrect and false alarms of one detection method by using another detection method [17]. According to the mentioned cases, in order to detect intrusion in the power grid, we employed the AdaBoost algorithm and the particle swarm optimization algorithm.

4 METHODOLOGIES

AdaBoost was employed as an ensemble classifier to combine multiple weak learners, where each learner focused on misclassified instances from previous iterations. This approach improved detection stability after feature reduction using PSO [16], [17].

In this work, it is proposed to use the AdaBoost classifier to achieve the goal of increasing detection accuracy in order to detect intrusion in smart grids. The advantage of this approach over other methods is that this algorithm is an ensemble learning method. In ensemble learning algorithms, an example is classified using several different classifiers, and the result of the classification is intelligently combined with each other, and the final result is determined for that specific example [26]. The accuracy and performance of this algorithm is higher compared to traditional and deep classification algorithms, because the general result is obtained from several classifiers. This algorithm has reduced the error and variance of training data.

In ensemble learning algorithms, each classifier is trained with a randomly selected subset of all samples. With the formation of several different classifiers, the final classifier, which is the result of a collective view, contains more efficiency [17]. Also, to increase the efficiency of this classifier, we intend to select the best features using the particle swarm optimization algorithm, and then the selected features will be provided to the classifier as input [16].

5 PROBLEM STATMENT

Smart power grids are a very important issue in order to meet future energy needs [1]. In order to achieve higher efficiency, which is the goal of energy distribution networks of future generations, it is necessary to create a centralized energy source by integrating various distributed power plants, and to continuously manage and monitor energy production and consumption [23], [24]. In order to successfully accomplish this, it is very important to use special network monitoring techniques and utilize specialized application software [2].

Smart grid is a term that includes various aspects of modern electric power transmission and distribution networks [1]. In order to become familiar with the basic concepts of the smart grid, we will state some definitions that have been provided by reliable institutions:

The European Smart Grid Task Force and the SG European Technology Platform define smart grids as follows: electric grids that efficiently monitor the operation of all users of this grid, including generators, consumers, and production and consumption systems, in order to ensure high economic efficiency, stability of a powerful network with the lowest losses and the highest quality, security, and convenience of energy production [23].

In the United States, the U.S. Department of Energy's Power Transmission and Distribution Administration defines the future energy grid as: a network of digital technology used to increase the reliability, security, and efficiency of electric power systems [23]. This action is possible by using information exchange, distributed generators, and energy storage resources. These systems are created by using two-way communication technology and complex computer processes [2], [24].

According to the above definitions, telecommunication technology and information systems are very important in smart grids. For example, computer-based remote control, monitoring processing, industrial automation, two-way communication between producer and consumer, and smart meters are among its components [1], [2]. Therefore, it can be stated that the smart power grid is actually a vast telecommunication and communication network that deals with energy production, transmission systems, and small and large networks located at the end of the line.

As with any communication network, network security is one of the important requirements in the communication infrastructure of smart networks, and it can be considered one of the biggest challenges of implementing smart power grids [3], [9]. Whenever the security of these networks is compromised, all the components of this smart network will be at risk and the provision of its services will be difficult [4], [10]. A problem in providing service in a part of smart networks means the power outage of several houses, factories, or even a city and several power plants being out of service. Considering the role that electricity has in people's lives, this issue has many serious consequences [1], [20].

6 DISCUSSIONS

The experimental results obtained in this study indicate that integrating PSO-based feature selection with the AdaBoost ensemble classifier enhances intrusion detection performance in smart grid environments [16], [17]. Reducing the feature set from 40 to 30 features eliminated redundant and less informative attributes, enabling the classifier to focus on the most discriminative traffic characteristics.

The ensemble learning nature of AdaBoost played a key role in improving classification stability by combining multiple weak learners, which reduced variance and mitigated misclassification errors [17]. This behavior is particularly beneficial in smart grid systems, where reliable and timely detection is critical due to the close interaction between cyber and physical components [15], [30].

Although the achieved accuracy of 92.9% demonstrates the feasibility of the proposed approach, the results should be interpreted in the context of the employed dataset and experimental setup. The findings confirm that optimization-based feature selection can effectively support ensemble classifiers in intrusion detection tasks, while also highlighting the importance of balanced evaluation beyond accuracy alone [17], [31].

7 LIMITATIONS AND FUTURE WORK

Despite the promising results achieved in this study, several limitations should be acknowledged. First, the experimental evaluation was conducted using a single benchmark dataset, which may not fully capture the complexity and diversity of real-world

smart grid traffic [29], [30]. Second, the proposed intrusion detection framework was evaluated in an offline setting, without considering real-time constraints or deployment challenges [7], [8]. Additionally, the PSO-based feature selection process prioritizes optimization performance over feature interpretability, making it difficult to directly associate selected features with specific attack behaviors [16].

Future work will focus on evaluating the proposed approach using real-world smart grid datasets [11], [18], extending the framework to multi-class attack scenarios [19], and investigating lightweight or adaptive optimization techniques suitable for real-time intrusion detection in large-scale smart grid infrastructures [28], [31].

8 RESULTS

The reported accuracy should be interpreted in the context of the NSL-KDD dataset and limited baseline comparisons. While the results demonstrate the feasibility of combining PSO with AdaBoost, broader comparisons with additional modern methods are left for future work. To check the effectiveness of the proposed method, we compared the results obtained from the test dataset of the proposed method with other methods reported in the baseline article, as summarized in Table 1. It should be noted that the dataset used in this work is the same as the dataset used in the baseline paper.

Table 1: Comparing the results of different methods with the proposed method.

Method	Accuracy	Precision
XGBOOST	89,15%	80,27%
LSTM_XGBOOST	89,21%	82%
AdaBoost+PSO	92,9%	88%

9 DATA SET USED

To evaluate the performance of the proposed intrusion detection system, accuracy, precision, and recall were employed as evaluation metrics [17], [31]. Accuracy was used to assess the overall effectiveness of the proposed PSO–AdaBoost framework in correctly classifying both normal and intrusive traffic. Precision was considered essential due to the critical nature of smart grid environments, where excessive false alarms may lead to unnecessary operational interventions [10], [30]. Recall was used to measure the system's ability to correctly detect actual intrusion instances, ensuring that malicious activities were not overlooked. These metrics were jointly analyzed to provide a balanced assessment of detection capability and system reliability [31].

10 CONCLUSIONS

The increasing dependence on electricity and the growing complexity of smart power grids highlight the critical importance of ensuring their security. Smart grids rely heavily on communication networks that enable two-way data exchange and integration of various system components. However, this interconnected and distributed structure also introduces new vulnerabilities, making such systems attractive targets for cyber-attacks. The integration of SCADA and ICT technologies further increases exposure to potential cyber risks.

To address these challenges, this study proposed a hybrid intrusion detection approach that combines Particle Swarm Optimization (PSO) for feature selection with the AdaBoost ensemble learning algorithm. After applying preprocessing techniques, including data cleaning and normalization, PSO was used to identify the most informative subset of 30 features from the original 40 features. The reduced feature set was then used to train the AdaBoost classifier, improving detection efficiency and reducing redundancy.

The results demonstrate that the proposed approach achieves a classification accuracy of 92.9%, outperforming the baseline method by approximately 3%. These findings confirm that integrating optimization techniques with ensemble learning can significantly enhance intrusion detection performance in smart grid environments.

Overall, the study highlights the potential of combining feature selection and ensemble methods as an effective solution for improving the security and reliability of modern smart power systems.

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Mathematical Foundations for Modeling and Scaling of Dynamic Systems

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Keywords: Dynamic Systems, State-Space Models, Similarity Transformations, Scaling Methods, Electric Vehicles, Model Reduction, Control-Oriented Modeling.

Abstract: The increasing complexity of electric vehicle (EV) powertrains – integrating multi-domain interactions among traction motors, battery packs, and power electronics – demands mathematically rigorous yet computationally efficient modeling frameworks. This paper presents a structured review of the mathematical foundations for modeling and scaling of dynamic systems, with emphasis on EV applications. Three core analytical tools are examined in depth: 1) state-space representation as a unified multi-domain modeling formalism; 2) similarity transformations for complexity reduction while preserving essential system invariants such as eigenvalues, characteristic polynomials, and transfer functions; and 3) scaling techniques, including dimensionless parameterization and transfer function normalization, for cross-platform simulation efficiency. A structured mapping links these methods to specific EV subsystems: traction motors (4th–8th order systems), battery packs (2nd–10th order equivalent circuits), and power inverters (3rd–6th order systems), identifying the most appropriate scaling strategy for each. The reviewed framework supports scalable simulation, model-based diagnostics, and control system design, bridging high-fidelity physics-based models and computationally efficient representations required for real-time embedded applications. This paper serves as a foundational methodological resource for researchers and practitioners in EV engineering and control systems.

1 INTRODUCTION

The rapid global expansion of electromobility, driven by environmental regulation and the broader transition to sustainable energy, has substantially increased the engineering complexity of electric vehicle (EV) powertrain systems. Modern EVs integrate tightly coupled subsystems – traction motors, power electronic inverters, electrochemical battery packs, and mechanical drivetrains – each operating across different physical domains and timescales [1]. The co-simulation of these subsystems within a single unified framework represents a fundamental challenge in contemporary systems engineering.

Effective analysis, design, and validation of such multi-domain dynamic systems require mathematical modeling tools that are simultaneously expressive, computationally tractable, and scalable across a range of component sizes and operating conditions. Three methodological pillars have emerged as particularly relevant in this context: state-space representation, similarity transformations, and signal scaling techniques.

State-space models provide a compact and general formalism for representing linear and nonlinear dynamic systems of arbitrary order, enabling systematic treatment of controllability, observability, and stability [2]. Unlike transfer-function approaches restricted to single-input single-output (SISO) descriptions, state-space methods naturally accommodate multi-input multi-output (MIMO) configurations typical of EV powertrains, where cross-coupling between flux, torque, voltage, and current dynamics must be explicitly captured [3].

Similarity transformations constitute a second essential tool. By applying invertible coordinate changes in the state space, it is possible to decompose complex high-order systems into canonical or

decoupled forms, substantially simplifying analysis and controller synthesis while guaranteeing the preservation of fundamental dynamic invariants [4]. For EV motor models, this allows independent treatment of flux and torque channels; for battery models, it enables the isolation of dominant electrochemical modes.

Scaling and dimensionless parameterization form a third indispensable layer of the framework. When the same control algorithm must be deployed across motors of different rated powers, or when battery models must generalize across different cell chemistries, re-deriving the full mathematical model for each configuration is computationally prohibitive. Scaling techniques allow systematic reformulation of system equations into normalized forms, from which platform-specific models can be recovered by simple parameter substitution [5].

The integration of intelligent monitoring and condition-based diagnostics into EV operation further amplifies the need for scalable dynamic models. Real-time fault detection – whether based on spectral analysis, wavelet decomposition, or data-driven approaches – relies on efficient model representations that can be executed on embedded control hardware [6], [7]. Providing such representations without sacrificing physical fidelity is a central open problem in applied systems modeling.

This paper reviews the mathematical foundations underpinning these three modeling paradigms and demonstrates their structured applicability to EV components. Section 2 develops the theoretical framework, covering state-space models, the matrix exponential solution, transfer functions derived via the Laplace transform, and the formal theory of similarity transformations. Section 3 presents scaling methods and their canonical dimensionless formulations. Section 4 discusses the practical mapping of these methods to specific EV subsystems, supported by a comparative summary table. Section 5 concludes with recommendations for future research directions. This study reviews mathematical approaches to modeling and scaling of dynamic systems, with particular attention to their applicability in electric vehicle (EV) powertrain analysis.

2 MATHEMATICAL FRAMEWORK

2.1 State-Space Representation of Dynamic Systems

A continuous-time linear time-invariant (LTI) dynamic system is described in state-space form as:

$$\dot{x}(t) = Ax(t) + Bu(t),\ y(t) = Cx(t) + Du(t) \quad (1)$$

where $x(t) \in \mathbb{R}n$ is the state vector, $u(t) \in \mathbb{R}m$ is the input, $y(t) \in \mathbb{R}p$ is the output, and A, B, C, D are real system matrices of appropriate dimensions. Electrical, mechanical, thermal, and electrochemical subsystems of an EV.

2.2 Solution of the State Equation

The homogeneous solution $\dot{x} = Ax$ with initial condition $x(0) = x_0$ is derived from the power-series ansatz:

$$x(t) = \sum_{i=0}^{\infty} K_i t^i x_0 \quad (2)$$

Substituting into the differential equation and matching coefficients yields $K_i = A^i/i!$, so that the solution takes the form of the matrix exponential:

$$x(t) = e^{At}x_0 = \lim_{k\to\infty} \left(I + \frac{At}{k}\right)^k x_0 \quad (3)$$

In the discrete-time approximation with sampling interval h, this becomes:

$$x(t+h) \approx (I + Ah), x(t), x(0) = x_0 \quad (4)$$

Equation (4) constitutes the basis for numerical integration of state-space models and is directly implemented in simulation environments such as MATLAB/Simulink for real-time EV control applications [2].

2.3 Transfer Function Derivation via the Laplace Transform

Applying the Laplace transform to (1) under zero initial conditions yields the algebraic system:

$$sX(s) = AX(s) + BU(s), Y(s) = CX(s) + DU(s)$$

Solving for $X(s)$ and substituting:

$$\mathrm{Y}(s) = [C(sI - A)^{-1}B + D]\mathrm{U}(s) = \mathrm{G}(s), \mathrm{U}(s) \quad (5)$$

The matrix $G(s) = C(sI - A)^{-1}B + D$ is the transfer function matrix of the system. For a stable system driven by a harmonic input $u(t) = ae^{j\omega t}$, the Cauchy integral formula yields the steady-state frequency response:

$$\tilde{y}(t) = C(j\omega I - A)^{-1}B, \tilde{u}(t) \quad (6)$$

so that the matrix frequency transfer function takes the form:

$$G(j\omega) = C(j\omega I - A)^{-1}B \quad (7)$$

Each scalar entry $g_{ki}(j\omega)$ of this matrix establishes the relationship between the i-th harmonic input and the k-th output component of the steady-state response:

$$\tilde{y}k(t) = |gki(j\omega)|, a\cos(\omega t + \phi), \quad \phi = \arg g_{ki}(j\omega) \tag{8}$$

This frequency-domain characterization is the analytical basis for vibro-acoustic and spectral diagnostics of EV drivetrain components [6].

2.4 Similarity Transformations

A similarity (coordinate) transformation $x = T\tilde{x}$, where $T \in \mathbb{R}^{\mathbb{m}\times\mathbb{m}} with \det T \neq 0$, maps the original system matrices to an equivalent representation:

$$\tilde{A} = T^{-1}AT, \quad \tilde{B} = T^{-1}B, \quad \tilde{C} = CT, \quad \tilde{D} = D \tag{9}$$

The following four properties are invariant under any similarity transformation [4]:

1) Eigenvalues of A: $\lambda_i(\tilde{A}) = \lambda_i(A)$;
2) Determinant: $\det(\tilde{A}) = \det(A)$;
3) Trace: $(\tilde{A}) = (A)$
4) Transfer function: $\tilde{G}(s) = C(sI - A)^{-1}B + D = \tilde{C}(sI - \tilde{A})^{-1}\tilde{B} + \tilde{D}$.

These invariance properties ensure that similarity transformations yield a physically equivalent – but mathematically simpler – description of the system. A canonical choice of T leads to the companion (Frobenius) form, in which matrix A takes the structure:

$$A = \begin{matrix} 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \lfloor -a_n & -a_{n-1} & -a_{n-2} & \dots & -a_1 \rfloor \end{matrix} \tag{10}$$

The characteristic polynomial of A_c is:

$$\phi(\lambda) = \det(\lambda I - A_c) = \lambda^n + a_1\lambda^{n-1} + \dots + a_{n-1}\lambda + a = \sum_{i=0}^{n} a_i\lambda^{n-i}, \quad a_0 = 1 \tag{11}$$

The companion form (10) is particularly useful for order reduction: by truncating states associated with fast, weakly observable or weakly controllable modes, a reduced-order model is obtained that preserves the dominant dynamics of the original system [5].

3 SCALING METHODS FOR DYNAMIC SYSTEM MODELS

3.1 Motivation for Scaling

When a mathematical model of an EV subsystem must be reused across configurations that differ in rated power, voltage, or capacity, direct reuse of the original model is generally not possible without re-identification of all parameters. Scaling provides a systematic methodology for normalizing system variables and equations, enabling the derivation of dimensionless models that are configuration-independent [5].

3.2 Signal Scaling and Dimensionless Parameterization

Consider the original (dimensional) input-output description of a controlled process:

$$\hat{y} = \widehat{G\hat{u}} + \widehat{G_d\hat{d}}, \hat{e} = \hat{y} - \hat{r} \tag{12}$$

where $\hat{u}, \hat{d}, \hat{y}, \hat{e}, \hat{r}$ are, respectively, the control input, disturbance, output, error, and reference signals, all in physical (dimensional) units. Introducing diagonal scaling matrices $D_{,}D_{,}D$ such that the normalized signals

$$d = D_d^{-1}\hat{d}, u = D_u^{-1}\hat{u}, e = D_e^{-1}\hat{e}, r = D_u^{-1}\hat{r} \tag{13}$$

have unit magnitude bounds, the system is transformed into the dimensionless form:

$$y = Gu + G_d d, e = y - r \tag{14}$$

where the scaled transfer matrices are given by:

$$G = D_e^{-1}\hat{G}, D_u, G_d = D_e^{-1}\widehat{G_d}, D_d \tag{15}$$

The dimensionless formulation (14)–(15) is particularly advantageous for MIMO control system design, since all variables are of comparable magnitude, improving the numerical conditioning of matrix operations such as singular value decomposition and H_∞ norm computation [3], [5].

3.3 Scaling of Elementary Dynamic Links

Any *n*-th order LTI system with a single input and single output can be decomposed into a block diagram containing only amplifying (gain), integrating, and summing elements. The state-space matrices of such a decomposition can be obtained directly from the

companion form (10) via similarity transformation, allowing systematic construction of scaled block diagrams for EV subsystems of arbitrary order.

For systems with serial, parallel, or feedback interconnections of elementary dynamic links Σ_1 and Σ_2, the composite state-space matrices can be derived analytically [2]:

Series connection:

$$A = \begin{bmatrix} A_1 & 0 \\ B_2 C_1 & A_2 \end{bmatrix}$$

Parallel connection:

$$A = \begin{bmatrix} A_1 & 0 \\ 0 & A_2 \end{bmatrix}$$

Feedback connection: composed via the standard well-posedness conditions on the feedback loop.

These compositional rules enable modular construction of multi-domain EV powertrain models from independently validated subsystem models.
Scaling is especially effective when designing control systems for complex dynamic objects of the MIMO class.

4 APPLICATION TO ELECTRIC VEHICLE SYSTEMS

4.1 Structured Mapping of Methods to EV Components

Table 1 provides a structured mapping of the mathematical methods reviewed in Sections 2 and 3 to the principal dynamic subsystems of an electric vehicle powertrain. For each subsystem, the typical model order, the recommended scaling approach, and supporting references are indicated.

Table 1: Application of scaling and transformation methods to EV powertrain components.

EV Component	System Order	Scaling Method	Reference
Traction motor	4–8	State-space similarity transformation	[7]
Battery pack	2–10	Dimensionless parameterization	[20]
Power inverter	3–6	Transfer function scaling	[21]

4.2 Traction Motor Modeling

A permanent magnet synchronous motor (PMSM) or induction motor (IM) is typically represented in the synchronously rotating $d-q$ reference frame as a 4th to 8th order LTI system, with state variables comprising the d- and q-axis flux linkages (or currents), rotor speed, and, in higher-order formulations, mechanical oscillation modes of the drivetrain [7]. The state-space form is:

$$\dot{x_m} = A_m x_m + B_m u_m, y_m = C_m x_m$$

where $x_m = \left[i_d, , i_q, , \omega_r, , \theta_r\right]^\top$ for a 4th-order PMSM model. The application of a similarity transformation T that block-diagonalizes A_m allows independent tuning of the flux-weakening and torque-production channels, forming the analytical basis of field-oriented control (FOC) [7].

4.3 Battery Pack Modeling

Battery packs are commonly represented by equivalent circuit models (ECM) consisting of an open-circuit voltage source, an ohmic resistance, and one or more RC parallel branches capturing diffusion dynamics. A second-order (1-RC) ECM takes the state-space form with $x_b = [V_{RC}, , \mathrm{SoC}]^\top$, while higher-order (up to 10th order) models include additional RC branches and thermal states. Dimensionless parameterization is obtained by normalizing voltages by the nominal open-circuit voltage V_0 and currents by the rated capacity Q_n, yielding a normalized model in the form of (14)–(15) that is independent of cell chemistry and applicable across battery chemistries via parameter re-identification alone [20].

4.4 Power Inverter and Control Unit

A three-phase voltage source inverter (VSI) with its PWM controller is typically characterized by a 3rd to 6th order transfer function model, capturing the effects of switching delays, LC filter dynamics, and current control loop bandwidth. Transfer function scaling – achieved by normalizing frequencies to the inverter switching frequency ω_{sw} and gains to the DC-link voltage V_{dc} – enables a single normalized controller design to be deployed across inverters of different power ratings by straightforward rescaling of gains, without altering the control structure [21].

4.5 Interconnection and Scalable Simulation

The modular interconnection rules described in Section 3.3, combined with the scaled subsystem models of Sections 4.2–4.4, enable the construction of a full-vehicle powertrain model of controllable complexity. By selecting the appropriate truncation level in the companion form (10) for each subsystem, a hierarchy of models – from detailed design models (high-order) to real-time embedded models (low-order) – can be derived within a unified mathematical framework. This approach is directly supported by MATLAB Control System Toolbox and Simulink environments [2], [20].

5 DISCUSSION

5.1 Comparative Evaluation of Scaling Approaches

The three scaling paradigms reviewed in this paper – similarity transformation, dimensionless parameterization, and transfer function normalization – are complementary rather than competing. Similarity transformations operate on the internal representation of the system and are best suited for analytical tasks such as decoupling, controllability decomposition, and order reduction. Dimensionless parameterization, by contrast, operates on the external signal variables and is most effective when the same model structure must be reused across a family of physically similar but differently sized components, as in battery pack scaling across different cell counts. Transfer function normalization occupies an intermediate position, making it particularly appropriate for controller synthesis tasks where frequency-domain performance specifications (bandwidth, gain margin, phase margin) are defined in normalized units.

5.2 Implications for Model-Based Diagnostics

The framework presented here has direct implications for real-time condition monitoring and fault diagnosis in EV systems. Scalable state-space models provide a natural basis for observer design (Kalman filters, Luenberger observers) that can track the evolution of internal states – such as battery state-of-charge (SoC), state-of-health (SoH), or motor winding temperature – without direct measurement [6]. Deviations of the observer-estimated states from the actual measured outputs serve as residuals for fault detection [12]. The use of dimensionless parameterization ensures that the same observer algorithm can be applied across EV variants of different rated capacities, which is a significant practical advantage in fleet-level diagnostics.

Furthermore, when combined with spectral and wavelet analysis of motor current or vibration signals, the state-space framework supports the extraction of diagnostic features that are directly linked to the physical parameters of the mathematical model – such as changes in inductance due to winding faults or changes in the RC time constants of a battery equivalent circuit due to aging [17], [18].

5.3 Limitations and Future Directions

Several limitations of the present framework merit acknowledgment. First, the analysis is restricted to linear time-invariant systems. In practice, EV components exhibit significant nonlinearities: magnetic saturation in motors, nonlinear open-circuit voltage characteristics in batteries, and switching nonlinearities in inverters. Extensions to linear parameter-varying (LPV) or bilinear state-space formulations are required to address these effects rigorously.

Second, the scaling methods discussed assume that the structural form of the model (number of states, interconnection topology) is fixed across the scaling range. For large-scale systems, topology changes may be necessary, requiring more advanced model order reduction techniques such as balanced truncation or Krylov subspace methods.

Third, the integration of data-driven and machine learning methods with the physics-based state-space framework represents a promising avenue for future research. Hybrid models that combine first-principles structure with data-driven parameter identification [19] can potentially overcome the limitations of purely analytical approaches, particularly for aging battery packs or mechanically worn motor bearings, where first-principles parameter values are difficult to maintain accurately over the component lifetime.

6 CONCLUSIONS

This paper has presented a structured review of the mathematical foundations for modeling and scaling of dynamic systems, with application to electric vehicle powertrains. The following conclusions are drawn:

1) State-space representation provides a unified and computationally tractable framework for multi-domain EV modeling. The matrix exponential solution, companion canonical form, and transfer function derivation via the Laplace

transform collectively constitute the analytical core of this approach.

2) Similarity transformations enable complexity reduction while rigorously preserving four fundamental system invariants: eigenvalues, determinant, trace, and transfer function. Their application to traction motor models supports field-oriented control design and dynamic decoupling.
3) Scaling methods – including dimensionless parameterization and transfer function normalization – facilitate the systematic reuse of validated models across component families of different sizes, eliminating the need for full re-identification. A structured mapping of these methods to EV subsystems (Table 1) demonstrates their practical applicability.
4) The reviewed framework directly supports scalable simulation, model-based diagnostics, and embedded control design, bridging the gap between high-fidelity physics-based models and computationally efficient representations required for real-time operation.

Future work should address the extension of these methods to nonlinear and linear parameter-varying (LPV) system classes, as well as their integration with machine learning-based parameter identification and fault prognosis algorithms. Practical implementation can be carried out within the MATLAB/Simulink environment using the Control System Toolbox and Simscape Electrical libraries.

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Evaluation of GMA Civil Registrar Online Transaction System

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Keywords: Civil Registrar, Online Transaction System, Functionality, Public Service.

Abstract: This study developed an application for Online Transactions in the General Mariano Alvarez, Cavite Civil Registrar. This application has features that allow users to access the Emergency Hotlines, Announcements, Information about the Civil registrar, and booking of appointments. The GMA Civil Registrar Online Transaction System can help facilitate the obtaining of certificates such as Birth, Marriage, Death, and CENOMAR (Certificate of No Marriage Record), and set an appointment for other services. The evaluators of the system are the IT experts, IT students, Municipal Civil Registrar Office (MCRO) staff, and walk-in clients of General Mariano Alvarez (GMA), Cavite. The research instrument used is based on ISO 25010 evaluation tools for application software. This study utilized the convenience sampling technique in selecting evaluators; the weighted mean and t-test are the statistical treatments used for this study. Based on the evaluation, the system got a verbal interpretation of "Strongly Acceptable" for its Functionality, Efficiency, Maintainability, Reliability, and Portability. Meanwhile, the profile of the evaluators as to gender and profession is found not significant, while gender is found significant to the maintainability of the application. It is suggested that the online payment system may be included for future enhancement.

1 INTRODUCTION

The growth in the mobile phone industry and mobile applications has been one of the important technological innovations in computing in this generation. These innovations support different aspects of daily living. The fast-paced advancement of computing devices known as the "digital era" has revolutionized a variety of applications and integration to different sectors, from communication, entertainment, education, security, business operations, and government services. This "digital era" has become indispensable equipment that gives the end-users more efficient, effective, reliable, and accessible services for a wide range of applications.

There is a need to be more empirical research on local e-governments. Based on evaluation and to operationalize the e-Government focus of the Philippine Digital Strategy, the E-Government Masterplan (EGMP) acknowledged the important role that ICT plays in fostering open and transparent government and the delivery of sufficient public services (Department of Information and Communication Technology, 2014). Implementation of e-government in the country has been in the planned of the government, thus [27] in their study, they investigate the adoption of e-government in the country, However, in developing countries like the Philippines, citizens face significant challenges in adopting e-government because of differences in socio-demographics, ICT access, Internet usage habits, and service awareness. The incorporation of E-government services is a vital lever for growth in the Philippines [17]. These innovative initiatives have been taken to improve public service delivery. Government services could be enhanced through e-government. The national e-government projects in the Philippines are still moving forward [2].

Various Civil Registry Document (birth certificates, marriage certificates, certificates of no marriage, death certificates, etc.) acquisition methods. They suggested an immediate, electronic, paperless, and more expedient alternative to the current procedures for obtaining Civil Registry Documents [28]. Moreover, physical distance and transportation challenges can hinder access to these essential services. Thus, these traditional methods, opted to involve in-person visits and lengthy paperwork and manual procedures, are likely to cause errors, delays, and inconvenience. The innovative solutions of this rapid technological evolution change the traditional delivery of services, including

government services. However Municipality of government agencies faced challenges in adopting digital solutions and innovations for their services, this leads to inefficiency of transaction, long waiting time and bureaucratic hurdles for the people [3], to achieve high performance and manage their business effectively and without time-consuming procedures, organizations frequently face challenges, such as the need to stay up to date with technological advancements. Civil registries, which are essential for various legal and administrative purposes, face challenges and issues. The limited accessibility of civil registry services, especially for individuals residing in remote areas or those with mobility impairments. Additionally, a lack of an online platform for requesting and obtaining vital documents.

The development of the GMA Civil Registrar Online Transaction System represents a significant leap toward modernizing public services.

1.1 Theoretical Framework

Guided by [16] theoretical framework, which emphasizes the relationship between citizens' needs and their engagement with government services, this research explores the application's ability to meet user demands efficiently. It addresses problems in need of innovative solutions that leverage technology to streamline government processes and improve citizen experience, making them faster, more reliable, and accessible. Mobile applications, in particular, offer to address the challenges faced by citizens when accessing essential civil registry services. By digitizing the request and issuance of documents such as obtaining certificates for birth, marriage, death, and CENOMAR, as well as booking appointments for other related services, these applications can significantly reduce wait times, minimize paperwork, and enhance transparency an application user to conduct transactions from the comfort of their homes.

1.2 Objectives of the Study

Designing, creating, and testing a mobile and online transaction system for the General Mariano Alvarez (GMA) Civil Registrar is the main goal of this study. By utilizing the benefits of information and communication technology (ICT), such as greater accessibility, higher efficiency, increased dependability, and shortened transaction times, this method seeks to modernize service delivery and overcome the drawbacks of conventional in-person procedures. Specifically, it aimed to (1) determine the profile of the respondents; (2) assess the respondents' evaluation based on ISO 25010 variables; and (3) determine the significant difference in the assessments of the respondents.

2 METHODOLOGY

This study used the descriptive developmental research, a developmental method, described as the methodical investigation of developing, manufacturing, and evaluating educational processes, goods, and programs that must satisfy the standards for efficacy and internal consistency. The purpose of the system was to design an online transaction system, through a mobile application for the Municipality of GMA Civil Registrar, that facilitates and addresses the challenges by digitizing all services of the office.

In the development of the application, an agile methodology approach was used; this approach to software development interleaves program planning, requirement analysis, design, development, testing, and deployment [6]. Every organization has incorporated agile software development into its everyday operations and modified its project development methodology [25]. It "evolved from the personal experiences and collective wisdom of consultants" rather than being created.



Figure 1: Model for agile software development.

Figure 1 illustrates the agile model, it includes planning, requirement analysis, design, development testing and deployment phase. Planning phase includes the careful analysis needed for this study. Requirement analysis is performed to ensure all the system and software requirements are aligned with the needs of the end-user. For getting relevant information, first the researcher requests permission from the GMA Civil Registrar office to conduct data gathering, and data are gathered within one one-

month time frame. The researcher collected data and demographic profiles (age, gender, and profession) from Walk-in Clients and Municipal Civil Registry Office (MCRO) Staff using an interview and survey questionnaire employing a convenience sampling technique, and a purposive sampling technique for IT Experts as evaluators of the system.

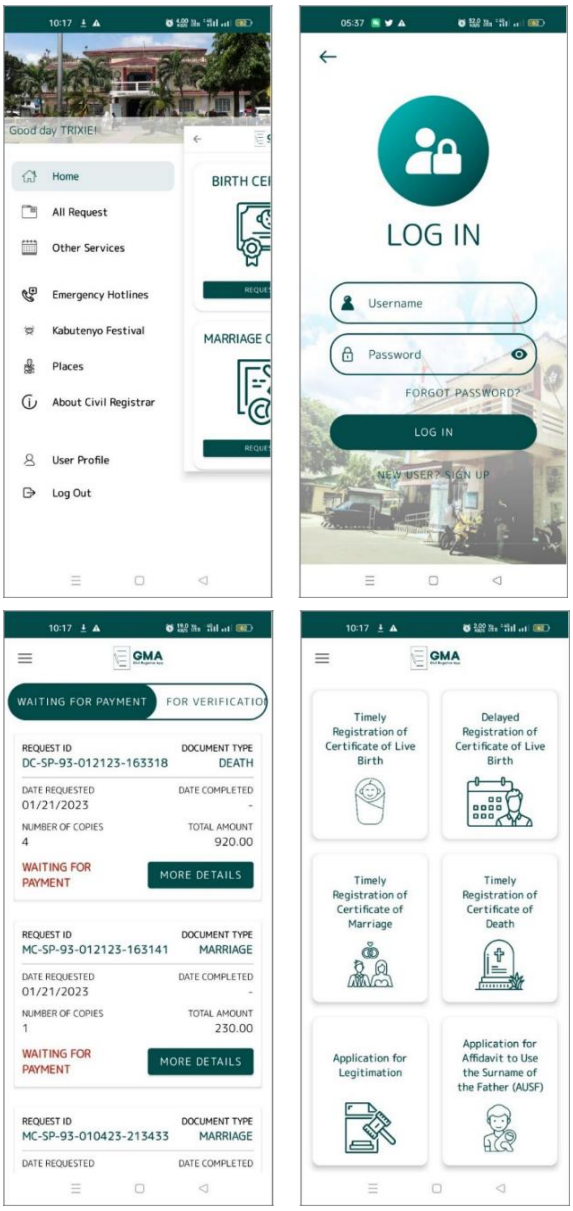


Figure 2: User interface of the mobile application for the online transaction system of the GMA Civil Registrar.

Figure 2 illustrates the sample user interface for mobile based application of the system, user need to register an account before it can see all the services provide by the civil registrar. The user can manage and see the status of every transaction.

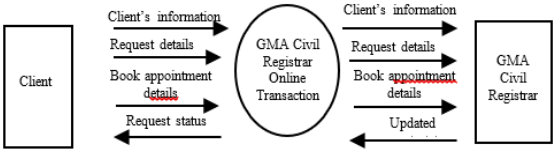


Figure 3: Context diagram of the GMA Civil Registrar Online Transaction System.

The design phase shows how the plan is to be taken into action according to the analysis phase. Figure 3 shows the context diagram of how the system works with the interaction of the user.

As show in the Figure 4 the user interface for administrator of the system. It indicates the admin dashboard and all the access of the system where the all management of transaction takes place.

The development phase is where the plans and design are executed through a series of programming and codes, these include the use of Java programming, HTML, XML for layout and resource files, and Firebase for the database. One of the critical parts of the process in the testing phase, the study employs system testing and integration testing for each module of the system. During deployment phases, the system will undergo a pre-launch of the system, and will undergo constant maintenance of the system. This part ensures that there is constant feedback from the user.

This study evaluates the application for its functionality, reliability, usability, efficiency, maintainability, and portability, these criteria are according to ISO 25010. ISO 25020 is an international standard that defines a framework for evaluating the quality of software and systems, providing a more thorough overview of the elements required to ensure software quality and deliver a positive experience to the consumer. It provides a structured way to define, measure, and evaluate software quality based on the above-mentioned criteria [26]. ISO 25010 is a reputable and well-established software quality management system that evaluates a software product's quality, which doesn't have to depend on gut feeling or personal preference [29]. Table 1 shows the 5-point Likert scale used for the assessment using ISO 25010.

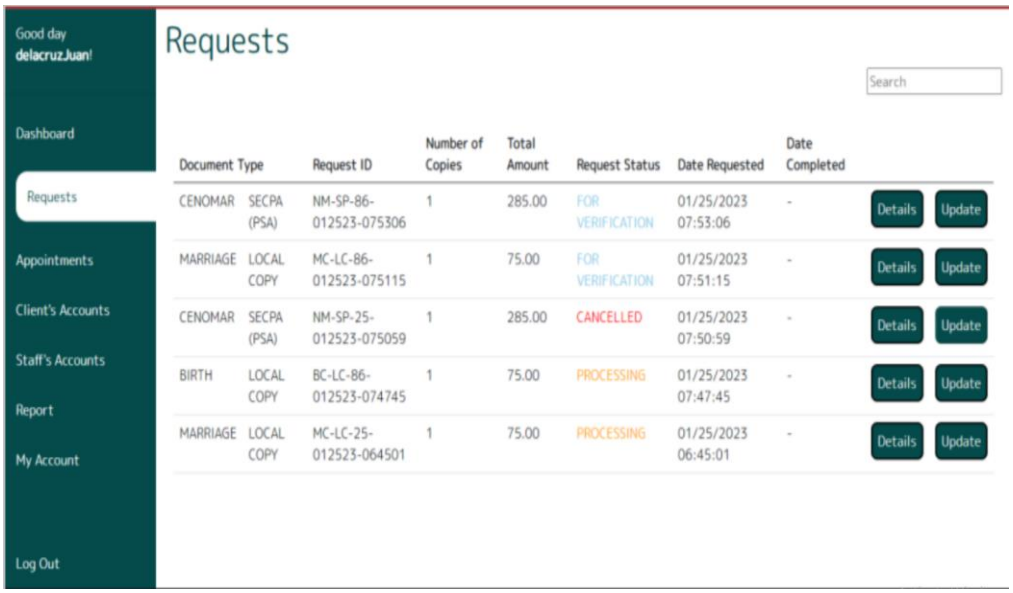


Figure 4: User interface of the web-based application for the online transaction system of the GMA Civil Registrar.

Table 1: 5-Likert Scale for assessment of the portal based on ISO 25010.

Rating	Scale	Verbal Interpretation
5.00	4.20 – 5.00	Excellent
4.00	3.40 – 4.19	Very Good
3.00	2.60 – 3.38	Good
2.00	1.80 – 2.59	Fair
1.00	1.00 – 1.79	Poor

For treating the data, frequency, percentage, rank, and weighted mean are used, and a t-test to determine the difference in the assessment of the system among the respondents in terms of the above-mentioned variables.

3 RESULTS AND DISCUSSION

Table 2 shows the summary profile of the evaluators. There were 51 or 65 percent of evaluators age group is 21 to 25 years old; 14 or 18 percent of evaluators age are under of 31 years old and above; while 13 or 17 percent of the evaluators are under the group of 26 to 30 years old. Male respondents comprised 46 or 59 percent of the evaluators, while 32 or 41 percent are females. There were 50 IT students, 85 clients, 11 IT experts, and 15 MCRO staff.

Table 3 shows the summary of assessment of the evaluators on the mobile application, where Portability has with computed mean of 4.67; As to Functionality and Maintainability with a computed mean of 4.64; Usability computed mean of 4.62; Reliability computed mean of 4.58, and Efficiency, with computed mean of 4.56 and all are Strongly Acceptable for its interpretation.

Table 2: Summary profile of the respondents.

Profile		Frequency
Gender	Male	32
	Female	46
Age	21-25 years old	51
	26-30 years old	13
	Above 31 years old	14
Profession	IT Experts	11
	IT Students	50
	MCRO Staffs	15
	Clients	85

Table 3: Summary of assessment on the application based on ISO 25010.

Rating	Mean	Verbal Interpretation	Rank
Functionality	4.64	Strongly Acceptable	2.5
Reliability	4.58	Strongly Acceptable	5
Usability	4.62	Strongly Acceptable	4
Efficiency	4.56	Strongly Acceptable	6
Maintainability	4.64	Strongly Acceptable	2.5
Portability	4.67	Strongly Acceptable	1
Grand Mean	4.62	Strongly Acceptable	

The assessment illustrated that the mobile application has a high level of acceptability from the end-users. E-government platform offers features that may provide customers with what they want, ranging

from making online services more accessible to connecting with other agencies [5]. This will aid in the development of "citizen-centric" services that prioritize improving access and providing critical services on a single platform.

When categorized by age, Table 4 displays the variations in the respondents' application evaluations. The computed p-values of 0.963, 0.775, 0.625, 0.682, 0.214, and 0.822 corroborate the data, which indicates that there was no significant difference between the evaluators' judgments of functionality, dependability, usability, efficiency, maintainability, and portability. Consequently, all of the null hypotheses were accepted.

When categorized by gender, Table 5 displays the variations in the respondents' application evaluations. Based on computed p-values of 0.599, 0.791, 0.880, 0.505, and 0.459, the data showed no significant difference between respondents' evaluations of the application's functionality, reliability, usability, efficiency, and portability. The null hypotheses were thus approved. In the meantime, the null hypothesis was rejected since the maintainability p-value was 0.044, which is below the significance level of 0.05.

As a result, respondents' evaluations of the application's maintainability varied significantly. Research suggests that gender plays a significant role in the maintainability and sustainability of technological systems, [13] the Hegemonic and heterogeneous gender-technology connections can be created through the mobilization of gendered knowledge and activity by technicians during the installation and maintenance of renewable energy technologies.

This finding is consistent with earlier research indicating that software maintenance practices are influenced by organizational and cognitive factors, such as genderization in software development. Gender dynamics influence the software development lifecycle, which could result in variations in how teams approach and maintain maintainability [20]. In a similar vein, [19] male and female developers use different approaches to program comprehension—males rely more on attention-switching, while females typically examine code entities more closely. These discrepancies support the current study's finding that maintainability is greatly impacted and imply that gender-related cognitive methods may play a role in disparities in maintenance outcomes.

Table 4: Variations in the respondents' evaluations when categorized by age.

Variables	p-value	Null Hypothesis	Interpretation
Functionality	0.963	Accepted	Not significant
Reliability	0.775	Accepted	Not significant
Usability	0.625	Accepted	Not significant
Efficiency	0.682	Accepted	Not significant
Maintainability	0.214	Accepted	Not significant
Portability	0.822	Accepted	Not significant

Table 5: Variations in the respondents' evaluations when categorized by gender.

Variables	p-value	Null Hypothesis	Interpretation
Functionality	0.599	Accepted	Not significant
Reliability	0.791	Accepted	Not significant
Usability	0.880	Accepted	Not significant
Efficiency	0.505	Accepted	Not significant
Maintainability	0.044	Rejected	Significant
Portability	0.459	Accepted	Not significant

Table 6: Variations in the respondents' evaluations when categorized by profession.

Variables	p-value	Null Hypothesis	Interpretation
Functionality	0.772	Accepted	Not significant
Reliability	0.319	Accepted	Not significant
Usability	0.895	Accepted	Not significant
Efficiency	0.941	Accepted	Not significant
Maintainability	0.219	Accepted	Not significant
Portability	0.903	Accepted	Not significant

When categorized by occupation, Table 6 displays the variations in the respondents' application evaluations. Based on computed p-values of 0.772, 0.319, 0.895, 0.941, 0.219, and 0.903, the data showed that respondents' evaluations of the application's functionality, dependability, usability, efficiency, maintainability, and portability did not differ significantly. Consequently, the null hypotheses were approved.

4 CONCLUSIONS

The majority of the assessors were male IT students between the ages of 21 and 25, the researchers deduced from the data they had collected. GMA Civil Registrar Online Transaction System obtained high rating for all criteria. While there were no significant differences in functionality, reliability, usability, efficiency, and portability across gender, age, or profession, there was a significant difference in maintainability ratings between male and female respondents. Although customers generally embraced the system, it is advised to make maintenance and efficiency enhancements to further maximize performance.

These benefits make the system more user-friendly, responsive to citizen needs, and adaptable for local government units (LGUs) looking to improve public service delivery. In contrast to previous studies on e-government and civil registry systems, which frequently concentrate on web-only platforms or limited service coverage, this research integrates both mobile and web access and offers multiple service features in a single application (emergency hotlines, announcements, information dissemination, appointment booking, and certificate requests).

5 RECOMMENDATIONS

Results reveal that when respondents are categorized by gender, their assessments of the variable maintainability differ significantly. The system recommends improvements that focus on refining the mobile application's maintainability features to ensure consistency and address the challenges faced by the clients. Even though there are no significant differences in the respondents' assessment when grouped by age and profession, the researchers highly recommend having a continuous evaluation and updates to maintain the strong acceptability of the application on the above-mentioned variables.

Additionally, to improve the accessibility of the system, it is recommended to have an IOS version to facilitate the expansion of the platform devices. The lack of an integrated online payment channel is one of the stated drawbacks and recommended for future development. Moreover, it is highly recommended to provide MCRO staff training sessions on the use of the mobile application to maximize its benefits, which will ensure the usability and satisfaction among the end-users. Furthermore, an integration with other E-government services to the mobile application for providing more comprehensive services, if applicable.

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AI-Driven FinTech: Accelerating Sustainable Development Goals and Economic Growth in the Philippines

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Keywords: Fintech, Artificial Intelligence, Digital Banking, Financial Inclusion, PRISMA, Systematic Literature Review, Sustainable Development Goals.

Abstract: The Philippines has emerged as a fintech hub powered by artificial intelligence in recent years, propelled by innovative governance, by broadening financial access, and a youthful, tech-inclined population. This flourishing AI-driven fintech environment has influenced Filipinos' banking services accessibility and spurred economic expansion and innovation, indirectly supporting the UN's sustainable development goals. Because more people use smartphones and the internet more frequently, many now view AI-driven fintech services as vital components of their daily lives. AI has made financial services and applications more customer-focused and technologically advanced; the increasing complexity of this dynamic setting is the primary reason for the recent rise in interest in this field. As a result, it is just logical to conduct an in-depth review of the relevant literature in this field. This research aims to summarize the significant AI-Fintech employed in the Philippines, analyze the benefits of applying and adopting AI-Fintech, outline fintech developments, possible risks, and disadvantages, analyze and evaluate possible challenges to the implementation of AI-Fintech in the Philippines, and provide recommendations to strengthen the bridge between academia, industry, and regulators. Finally, it aims to reveal research gaps in AI-driven financial technology.

1 INTRODUCTION

The introduction of technological advancements has had a significant impact on how we live our lives and on traditional methods of doing things, impacting transaction processing and data management. These technological advancements, such as cryptocurrencies, robo-advisors, and peer-to-peer lending, improved customer satisfaction, financial inclusion, and operational efficacy [1]. Complex financial operations brought about by fintech advancements amplify service efficacy [1].

In 2023, 72.2% of Filipinos used financial technology apps, totaling 59.3 million users [2]. Payments and transfers increased by 17.6%, e-wallets by 4.9%, and e-banking by 4.3% [2]. Fintech adoption reached 69.3% in 2022, driven by government support and market demand [2]. Online lending and e-wallets grew significantly [2].

The country's 2023 Fintech Report [3] highlighted 299 fintech firms, with payments leading the sector at 37%. Meanwhile, digital financial services have seen a decline from 27% to 21%, while lending comprises 20%, remittances account for 11%, and e-wallets make up 9% [4].

The most recent fintech report indicates significant growth in the industry, which has enhanced financial inclusion for unbanked Filipinos, supported by regulatory bodies. The Philippines has 441 rural banks, 48 thrift banks, and 46 universal and commercial banks, with total assets amounting to $385.6 billion [5]. Commercial banks dominate the banking sector, representing 92.8% of overall assets [5]. Prominent fintech firms such as CIMB, UNOBank, and GCash lead the electronic payments sector [5], [6].

Digital banking has revolutionized financial services through improved customer engagement and transaction efficiency [7]. The role of artificial

intelligence (AI) is vital in personalizing experiences and managing risks. Union Bank and Bank of the Philippine Islands are at the forefront of AI innovations, enhancing client satisfaction and streamlining operations [7]. Advancements in high-speed communication, data storage, and processing power have made AI implementation practical across various sectors, including healthcare, manufacturing, and finance [8]. Its adaptability has contributed to its widespread adoption in the banking sector [9].

The proliferation of data in the banking sector is expected to drive further AI integration. However, issues like data bias and other challenges can hinder full utilization, affecting customer trust and outcomes [10]. A reliance on external AI solutions can alienate customers, necessitating strategies like audits, transparent evaluations, and customer feedback to effectively address these challenges [11].

This study investigated the Philippines' use of AI-Fintech, how it could contribute to certain SDGs, examined the benefits, risks, and implementation challenges, and provided recommendations for stakeholders to foster innovation. The guiding question investigated whether the country's adoption of AI-driven FinTech can boost financial inclusion and innovation, and further the nation's economic growth.

2 RESEARCH METHOD

To guarantee a systematic review with improved quality control, this study adhered to the guidelines of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [12], which include identifying information sources, selecting studies, collecting data, and establishing eligibility criteria.

The study systematically collected and analyzed data and filtered unreliable publications via Scopus. Eligible papers were identified using specific keywords and reviewed in-depth based on title, abstract, and keywords.

The SLR collected data through manual study searches, screening, and analysis to extract key information on article type, journal, publication year, subject, methods, and outcomes. The inclusion criteria (IC) specified (IC1) original, peer-reviewed English studies (IC2) on factors affecting AI-driven fintech adoption and its economic impact, (IC3) using robust quantitative, qualitative, or mixed-methods.

Data items were selected based on specific criteria to ensure study consistency. Figure 1 presents the systematic literature review process. Out of 308 research publications, the selection process considered variables like title, abstract, and keywords, leading to 81 publications. Ultimately, 25 relevant articles emphasized the practical goals and contextual significance.

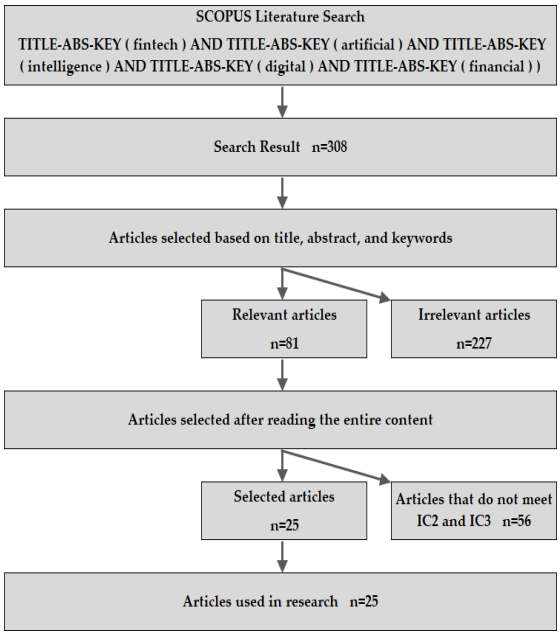


Figure 1: SLR reporting items (PRISMA Adopted).

3 RESULTS

A literature search identified 25 articles published between 2019 and 2025, organized into six groups: AI and fintech applications (15 articles), sustainability and financial inclusion (4 articles), adoption and impact (2 articles), and regulation and policy (4 articles).

Articles were categorized by primary focus, highlighting interests in areas such as financial risk management and robo-advisory services. Key issues include sustainability, financial inclusion, and regulations. A research gap exists on stakeholder effects, requiring further exploration. Table 1 highlights 25 articles on empirical analysis. The +Sig findings highlight the potential benefits and positive impacts of AI-driven fintech on various aspects of finance.

Table 1: Article analysis and synthesis.

No.	Reference	Scope	Method	Results
1	[13]	Analyzes how AI-FinTech transforms banking, focusing on payment systems for efficiency, security, customer experience and sustainability.	Mixed-method	+Sig
2	[14]	Analyzes FinTech and AI's roles in sustainable development, financial inclusion, and social responsibility.	Quantitative	+Sig
3	[15]	Investigates the effects of user characteristics and the human-like characteristics of robo- advisors on loyalty, trust, and financial well-being, aiming to enhance robo-advisory services.	Quantitative	+Sig
4	[16]	Examines fintech regulation's geopolitical impact, contrasting major powers' methods and addresses challenges in digital finance and AI.	Qualitative	+Sig
5	[17]	Examines AI adoption and financial access's role in China's energy sustainability, offering policy recommendations for green finance and responsible AI use.	Quantitative	+Sig
6	[18]	Explores technology adoption in Indian banking, focusing on FinTech innovations' benefits, challenges, and future implications for financial services.	Qualitative	+Sig
7	[19]	Evaluates the efficacy of blockchain and artificial intelligence in financial risk management for compliance and fraud detection.	Quantitative	+Sig
8	[20]	Explores the integration of sustainability in finance and digital accounting, highlighting the revolutionary potential of AI-enabled FinTech, identifying literature gaps, and developing comprehensive sustainability frameworks.	Qualitative	+Sig
9	[21]	Explores enhancing AI- supported Letter of Credit review methods to mitigate assessment risks and optimize checker capacity in trade finance.	Quantitative	+Sig
10	[22]	Develops statistical methods and fuzzy logic to improve long- term management of digital financial assets in Russia, Analyzing- price growth and trade volumes.	Quantitative	+Sig
11	[23]	Analyzes legal challenges of AI-FinTech in Tanzania's finance, offering recommendations for balanced regulation ensuring stability, Consumer protection, and ethics.	Qualitative	+Sig
12	[24]	Analyzes FinTech adoption trends in SMEs, its implications, and potential effects on traditional.	Quantitative	+Sig
13	[25]	Explores opportunities, challenges, and potential of agentic AI in FinTech, proposing a sustainable research agenda.	Qualitative	+Sig
14	[26]	Examines robo-advisory solutions for wealth management, behavioral finance, and investment decision- making, contributing to future research in India.	Qualitative	+Sig
15	[27]	Examines the research on sustainable finance and financial inclusion, focusing on emerging digital financial risks and strategies for promoting secure, inclusive systems.	Qualitative	+Sig
16	[28]	Explores behavioral biases affecting Gen Z investment decisions in India and examines how AI-led digital advisory services can mitigate these biases.	Quantitative	+Sig
17	[29]	Analyzes the relationship between emerging transactions, enhancing accuracy through attention mechanisms.	Quantitative	+Sig
18	[30]	Develops CL- BGAD, a framework for detecting anomalies in bipartite graphs, enhancing security and robustness in AI models.	Quantitative	+Sig
19	[31]	Explores NFT return and volatility statistics, developing predictive models using autoregression and AI to forecast prices based on macroeconom ic factors	Quantitative	+Sig
20	[32]	Aims to create the RR- ABiLSTM chatbot for precise financial query classification, enhancing contextual understanding and improving communication in accounting	Quantitative	+Sig
21	[33]	Aims to create and assess a GAGAN model for effective money laundering detection in bank transactions, enhancing accuracy through attention mechanisms..	Quantitative	+Sig
22	[34]	Examines factors affecting AI neo-banking service quality and their effects on brand experience, trust, and loyalty.	Quantitative	+Sig
23	[35]	Investigates enterprise generative AI's applications in HR management, fintech, and productivity, emphasizing team selection, hiring decisions, and employee satisfaction and performance.	Qualitative	+Sig
24	[36]	Investigates Random Forest's effectiveness in predicting financial distress in BSE firms using financial ratios and corporate governance for improved accuracy.	Quantitative	+Sig
25	[37]	Aims to synthesize knowledge on financial robo-advisor design through a literature review, identifying requirements and providing an implementation framework.	Qualitative	+Sig

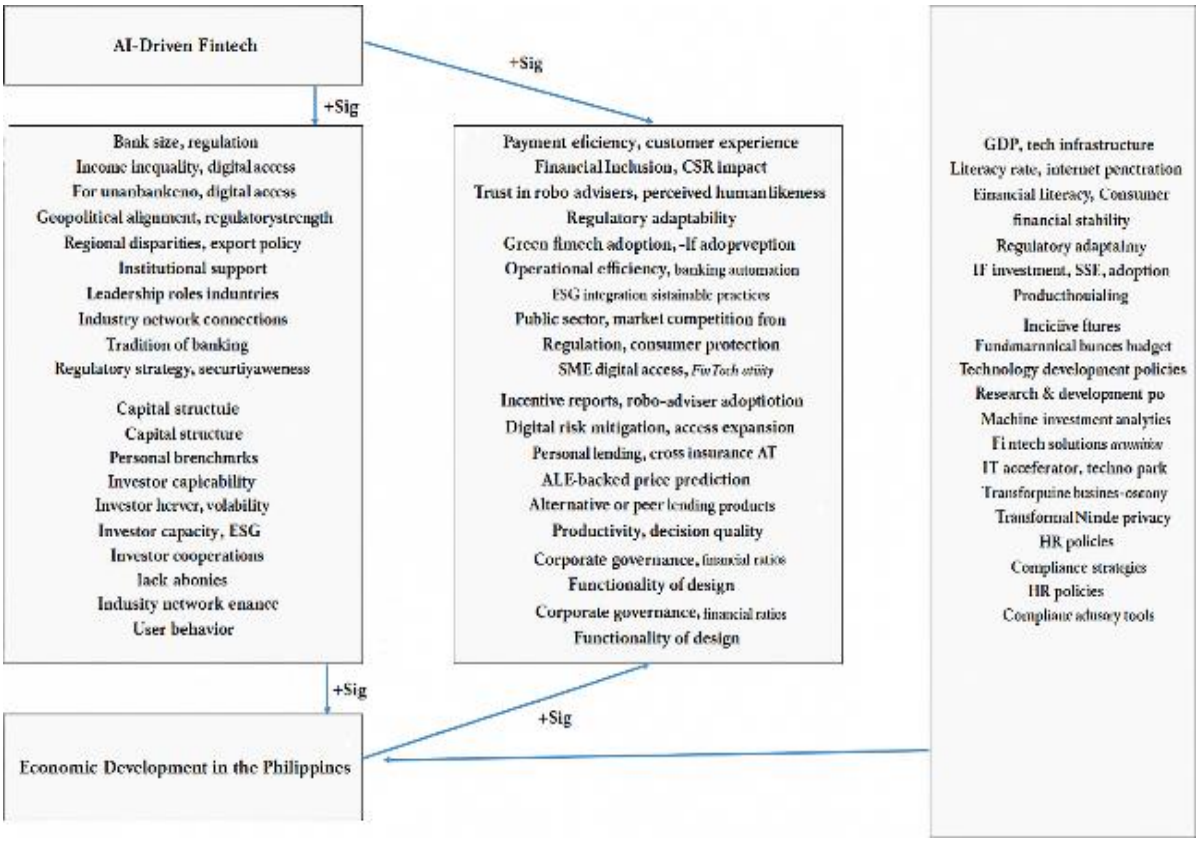


Figure 2: Research conceptual framework.

This research explored the theoretical ideals of the convergence of economic growth, technology, and finance, as rooted in Rogers' innovation diffusion theory [17], and explored the application of AI-driven FinTech in the Philippines, its wide-ranging effects on social and economic landscapes (Fig. 2).

The study also examined how AI-driven FinTech fosters economic growth and provides competitive advantages for businesses, grounded on the resource- based view (RBV) [38]. Additionally, it emphasizes the significance of easily accessible financial services and supports the theory of financial inclusion [39].

This study expands our understanding of the effects of AI-driven FinTech on financial inclusion and economic growth, notably in the underprivileged areas of the country.

Collaborations between traditional financial institutions and the emerging FinTech industry expand FinTech's ability to engage with the public and end-users, thereby helping to attain SDGs.

4 CONCLUSIONS

The Philippine fintech scene is in constant flux, driven by beneficial policies, inclusive finance programs, digital advancements, contactless payment solutions, and the integration of digital currency. The financial technology space remains strong, adapting to varied demands. With a solid standardized framework, it is ready for expansion, transformation, and inclusive finance.

The study looked at how AI-powered FinTech affected the nation, focusing on economic expansion, inclusive finance, transformation, strategic direction, and service quality enhancement. The outcomes can guide organizational direction and framework development, highlight growth prospects, and streamline financial processes. Possible approaches include investing in digital infrastructure, financial literacy programs, FinTech innovation centers, and standardized frameworks, thereby fostering economic growth and an entrepreneurial ecosystem.

There have been numerous studies on the impact of AI-FinTech on sustainable development and how it can accelerate the SDGs from various directions, but very few have examined AI-FinTech implementation initiatives and their effectiveness in furthering the SDGs. By providing resources and tools to deliver environmental and societal outcomes and encouraging inclusive finance, fintech companies help accomplish the SDGs. Therefore, companies' financial technology might be regarded as a stimulating way to create and deliver transformation.

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A Computational Framework for Optimal Control Using Polynomial-Based Approximation Methods with Applications in Intelligent Systems

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Keywords: Optimal Control Problem, Modified Vieta-Pell Functions, Direct Approximation Algorithms, Intelligent Robotic System, IT Applications.

Abstract: This work suggests an approximate direct technique to treat special kind of optimal control problem (OCP) in the finite domain [0, T] based on new modified family of Vieta-Pell functions. The proposed method employs a direct parameterization approach. In such technique, we approximate the state variables in terms modified family of Vieta-Pell functions and then transform the original optimal control problem to a constrained nonlinear programming problem. The aim of the presented algorithm is to reduce the numerical complexity with computational efficiency. The algorithm is well-suited for implementation in scientific computing environments such as MATLAB and Python, making it applicable to software-based control systems. To demonstrate its practical relevance to information technology applications, the proposed method is applied to optimal control problems arising in intelligent robotic systems, particularly robotic arm motion planning. Numerical simulations confirm fast convergence, high accuracy, and robustness, making the method suitable for integration into digital control architectures, intelligent automation systems, and IT-based robotic platforms.

1 INTRODUCTION

Optimal control problem (OCP) has been extensively considered in recent years. The major reason for the great importance of such problems are found in many applications in science, engineering, medicine, economics, finance, and a variety of other disciplines [1]-[3]. In recent years, the different algorithms to solve optimal control problem have been studied, such as the state parameterization technique with operation matrix of derivative for modified wavelets functions [4], the novel variational finite difference method [5], the difference method [6]-[7] and the finite element method to solve an OCP governed by e fractional wave equation [8], a wavelet collocation method for nonlinear partial OCP [9], Chebyshev wavelet and Müntz–Legendre Wavelet methods for solving various OCP [10-12], the Haar wavelet collocation method and Boubaker Wavelets [13]-[15]. The orthogonal functions are the most popular numerical approximates in solving an optimal control problem [16]-[18]. The ease and accuracy of applying the basic functions for treating an OCP and other many problems are our aim. Therefore, the authors in [19]-[21] extended solving different complicated problem based on numerical techniques together with the interesting basis functions called Vieta-Pell polynomials, such polynomials have utilized as a suitable technique for treating approximately a nonlinear fractional OCP [22]. A special Burgers an equation (BE) with fraction order was studied in [23] to solve BE approximately with the aid of certain family for Vieta Pell polynomials. In addition, the Vieta Pell polynomials are used in [24], [25] to solve stochastic fractional differential equations using direct technique. Some other work [26]-[29] used the generalized of Vieta Pell polynomials and their incomplete families.

The aim of the present work is the approximate investigation of the following optimal control problem:

$$\min J(x,u) = \int_0^T F(x(t),u(t),t)dt. \quad (1)$$

Subject to

$$\dot{x}(t) = g\big(x(t),u(t)\big), \quad (2)$$

and

$$x(0) = x_0, x(T) = x_T. \quad (3)$$

Here the two state and control vectors are $x(t)$ and $u(t)$ respectively.

The proposed modified version of the Vieta-Pell polynomials can use for many problems with finite intervals. In modern information technology applications, optimal control plays a vital role in intelligent systems such as robotics, autonomous platforms, embedded controllers, and cyber-physical systems. The effectiveness of these systems relies heavily on fast and accurate numerical algorithms that can be efficiently implemented in software environments. Consequently, developing computationally efficient basis functions and operational matrices is essential for real-time optimization and control. In this regard, the proposed MSIVP-based method provides a practical numerical framework that can be directly integrated into software-based control architectures used in intelligent robotic and IT-driven systems.

The paper is organized as follows. In Section 2, we introduce a new definition of MSIVP together with some interesting properties. In Section 3, we suggest a new approximated method to show how to transform an OCP (1-3) into an optimization one. We give two examples of our method in Section 4. In Section 5, the verification method on the IT applications is demonstrated and list conclusions in Section 6.

2 MODIFIED SHIFTED INCOMPLETE VIETA-PELL FUNCTIONS

In this section, we show how to modify the incomplete polynomials in [26] over limited domain to get an interesting basic functions on the domain $[0, T]$.

Definition 1. Let $M_n(t)$ denotes the modified incomplete Vieta Pell functions and s be any real positive numbers, then

$$M_n(t) = 2^s \left(\frac{2t}{T} - 1\right) M_{n-1}(t), n \geq 2, \quad (4)$$

where $M_1 = 1$.

In general, modified polynomials can draw as follows

$$M_n(t) = 2^{(n-1)s} \left(\frac{2t}{T} - 1\right)^{n-1}, n = 1, 2, ... \quad (5)$$

Some important properties are given in the next subsections to reduce the computations in working with new basis functions.

2.1 The MSIVP Product Operation Matrix

Theorem 1. Let $M_n(t)$ and $M_m(t)$ be as chosen in (4). Then for all $n, m \geq 1$, one has

$$M_n(t)M_m(t) = M_{|n+m-1|}(t). \quad (6)$$

Proof. Assume $n = 1$, then:

$$M_1(t)M_m(t) = M_m(t), m \geq 1. \quad (7)$$

Consider that $\{4\}$ is true for k, yields

$$M_k(t)\, M_m(t) = M_{|k+m-1|}(t). \quad (8)$$

We must prove that (4) is true for $k + 1$. By multiplying both sides of (8) by $2^s z$ to get,

$$2^s(z)M_k(t)\, M_m(t) = 2^s(z)M_{|k+m-1|}(t).$$

$z = \frac{2t}{T} - 1$ and making use of relation (4), which immediately gives

$$M_{k+1}(t)\, M_m(t) = M_{|k+m-1|}(t).$$

and this completes the proof of Theorem 1.

2.2 Operation Matrix of Derivative of MSIVP

Theorem 2. Assume that $M_n(t)$ as defined in (4). Then $\dot{M}_n(t)$, $n \geq 2$, can be defined in below

$$\dot{M}_n(t) = (n-1)\frac{2}{T}2^S M_{n-1}(t), n \geq 2\,. \quad (10)$$

Proof. Let $n = 2$, then $\dot{M}_2(t) = 2^S \frac{2}{T} M_1(t)$.

Assume that (10) is true for $(n - 1)$. Using (4), yields

$$\dot{M}_n(t) = 2^S \left[(z)\dot{M}_{n-1}(t) + \frac{2}{T} M_{n-1}(t)\right]. \quad (11)$$

Then from (4) one can get

$$\dot{M}_n(t) = M_2(t)\dot{M}_{n-1}(t) + 2^S \frac{2}{T} M_{n-1}(t). \quad (12)$$

Now, application of the induction step on $\dot{M}_{n-1}(t)$ in (12), yields

$\dot{M}_n(t) = (n-2)\frac{2}{T}2^S M_2(t)M_{n-2}(t) +$

$2^S \frac{2}{T} M_{n-1}(t)$.

It can simplify based on the results of theorem 1, to get

$$\dot{M}_n(t) = (n-2)\frac{2}{T}2^S M_{n-1}(t) + 2^S \frac{2}{T} M_{n-1}(t).$$

3 THE MSIVP ALGORITHM

The step by step MSIVP algorithm for the established method is outlined below.

Input: Initial position $(0) = x_0$, Desired final position $x(T) = x_f$, Final time $T = 1$, Approximation order n, Cost functional, Control definition.

Output: Approximate state trajectory $x(t)$, Approximate control signal $u(t)$, Optimal cost value J, Error norms L_2, L_∞.

Initialize MSIVP Basis Functions. Construct the MSIVP approximation of order n: $x_n(t) = \sum_{i=1}^{n} a_i 2^{(i-1)s}(z)^{i-1}$, Where $s = 1, T = 1$.

Compute the State Derivative. Evaluate the derivative:$\dot{x}_n(t)$

Define the Control Input.

Apply Boundary Conditions. Enforce: $(0) = x_0$, $x(T) = x_f$.

Formulate the Cost Functional. Substitute $x_n(t)$ and $u_n(t)$ into:

Solve the Optimization Problem. Minimize $J(a)$ subject to boundary constraints using a nonlinear programming solver to obtain the optimal coefficient vector: $a^* = (a, a_1, a_2, \ldots\ldots, a_n)$

Construct Optimal Trajectories. Substitute a^* into: $x^*(t) = u^*(t), x_n(t; a^*) = u_n(t; a^*)$

Compute Error Measures. Evaluate approximation accuracy using: $L_{2,z} = \sqrt{\sum_{j=1}^{N} |z_{ex.}(t_j) - z_n(t_j)|^2}$, $L_{\infty,z} = \max_j [z_{ex.}(t_j) - z_n(t_j)], j = 1, 2, \ldots, N$, where $z = (x, u)$.

4 NUMERICAL RESULTS

The accuracy of the proposed method is determined based on the following norms:

$$L_{2,x} = \sqrt{\sum_{j=1}^{N} |x_{ex.}(t_j) - x_n(t_j)|^2},$$
$$L_{\infty,x} = \max_j [x_{ex.}(t_j) - x_n(t_j)], j = 1, 2, \ldots, N.$$
$$L_{2,u} = \sqrt{\sum_{j=1}^{N} |u_{ex.}(t_j) - u_n(t_j)|^2},$$
$$L_{\infty,x} = \max_j [u_{ex.}(t_j) - u_n(t_j)], j = 1, 2, \ldots, N.$$

where $x_n(t)$, $u_n(t)$, $x_{ex.}(t)$ and $u_{ex.}(t)$ represent the approximate solution for the state variable, the approximate solution for the control variable, the approximate exact for the state variable and the exact solution for the control variable respectively. The absolute errors E for the performance index value is calculated using varies basis function orders as follow

$$E = |J_{ex.} - J_n|.$$

Here J_n and $J_{ex.}$ Represents respectively the approximate and exact cost values.

Example 1. In this problem, an object is to find the optimal control that minimizes

$$J = \int_0^1 (u^2 + x^2) dt.$$

Subject to $u(t) = \dot{x}(t)$,
Together with $x(0) = 0, x(1) = 0.5$.
while $x(t) = \frac{e(e^t - e^{-t})}{2(e^2 - 1)}$, $u(t) = \frac{e(e^t + e^{-t})}{2(e^2 - 1)}$ and $J_{exact} = 0.328258821379$ are the exact values for the state, control and the performance index value respectively.

The numerical results are obtained for both the state and the control variables at $n = 3,4$ and 5 and plotted in Figures 1 and 2. The analysis error norms are given in Tables 1 and 2.

Table 1: Errors for state of Example 1.

n	x(t)	
	L_2	Infinity norm
3	1.169575e-2	3.96544e-3
4	2.971882e-4	5.84650e-5
5	2.51801e-5	3.42773e-6

Table 2: Errors for control of Example 1.

n	u(t)		J
	L_2	Infinity norm	E
3	0.120678212	4.2881e-2	3.396e-4
4	5.110e-5	2.1836e-3	5.161e-7
5	9.4961 e-4	2.9811 e-4	9.330e-9

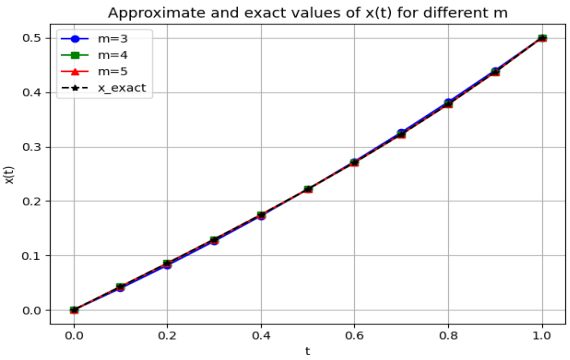


Figure 1: Approximate for state of Example 1.

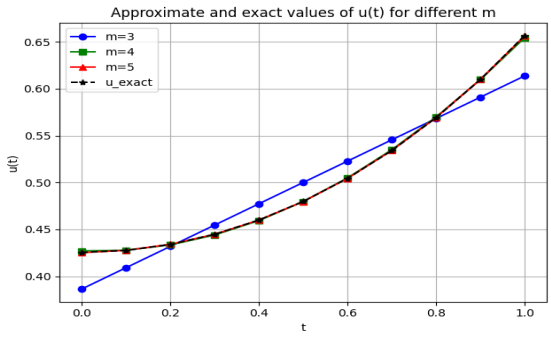


Figure 2: Approximate for control of Example 1.

A comparison is made between the present algorithm and the solution obtained by wavelets functions technique [4] for different values of n. It is based on the special wavelets basis functions to approximate the solution of the application 1 by using the state parameterization method. The absolute errors values E are respectively 0.000339663469485, 0.000000516182663 and 0.00000000933001 with $n = 3, 4, 5$. The advantages of the suggested incomplete technique on solving OCP is the ability for solving the OCP directly with the interval $t \in [0, T]$ while other methods must introduce a suitable transformation according to the base functions.

Example 2. The aim is to minimize the following performance index

$$J = \frac{1}{2}\int_0^2 u^2(t)dt, \quad 0 \le t \le 2,$$

with $u(t) = \dot{x}(t) + \ddot{x}(t)$ and $x(0) = 0, \dot{x}(0) = 0, x(2) = 5, \dot{x}(2) = 2$.

While $x(t) = K_1 + K_2 e^{-t} + C_1 t + \frac{C_2}{2} e^t$, $u(t) = C_1 + C_2 e^t$ is the exact solutions where $K_1 = -\frac{3e^4 - 2e^2 + 7}{4(e^2-1)}$,

$K_2 = \frac{e^2(1+3e^2)}{4(e^2-1)}$, $C_1 = \frac{7+3e^2}{4}$, $C_2 = \frac{7-3e^2}{2(e^2-1)}$.

$J_{exact} = 16.750723396861265$.

The obtained values of $L_{2,x}$. $L_{\infty,x}$, $L_{2,u}$. $L_{\infty,u}$ and E are illustrated at some selected n within the interval $t \in [0,2]$ and the results are given in Tables 3 and 4. In addition, Figures 3 and 4 plot the absolute errors for the state and control variables respectively.

Table 3: Errors for state of Example 2.

n	x(t)	
	L_2	Infinity norm
6	4.858775e-4	5.460372e-5
7	1.188900e-4	2.705501e-5
8	1.893695e-6	2.346852e-7

Table 4: Errors for control of Example 1.

n	u(t)		J
	L_2	Infinity norm	E
6	2.753e-2	4.129e-3	1.005e-5
7	1.420e-3	4.4723e-3	1.858e-8
8	2.706e-4	5.4293e-4	5.57e-10

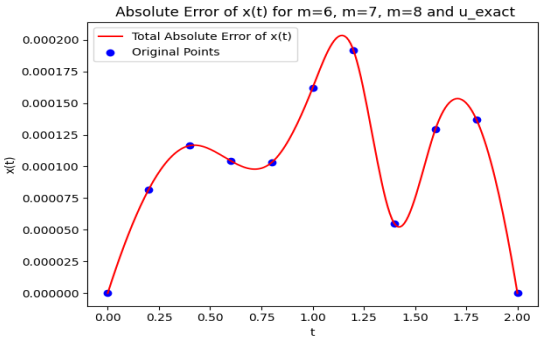


Figure 3: Absolute errors for state of Example 2.

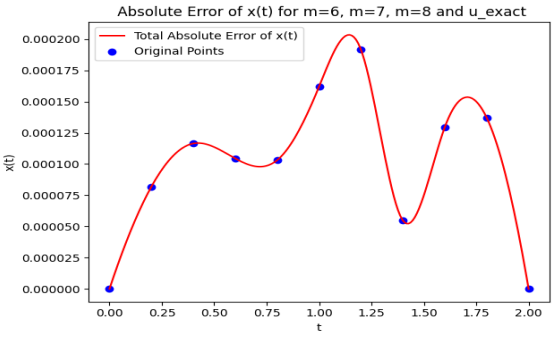


Figure 4: Absolute error for control of Example 2.

According to the Tables, as n increases, the values of E, L_2 and L_∞ decrease rapidly and the results reach to the exact values, the accuracy increases as the number of terms of the basis MSIVP expansion increases. Tables (1-4) illustrate that the suggested algorithm has a good convergence rate.

5 COMPUTATIONAL IMPLEMENTATION AND IT APPLICATION

The proposed MSIVP algorithm is developed with practical computational implementation as a primary consideration. Owing to the simplicity of the derived operational matrices, the algorithm can be efficiently implemented using standard scientific computing environments such as MATLAB, Python, and C-based numerical libraries which can allow the

algorithm to be useful for modern IT infrastructures. The presented modified basis functions can be used to find optimal state trajectory and control input in real time with a few computational cost of the suggested algorithm. Furthermore, the proposed technique can apply in simulation-based control design and enable the engineers to calculate the system performance with the aid of numerical simulations before real-world implementation. This illustrates the relevance of the suggested algorithm to applications of information technology, especially in robotic control software and intelligent automation,

5.1 The Formulation for Robotic Arm Motion Problem

Here, a robotic arm motion in one dimension is presented. The arm moves from the initial position $x(0) = 1$ to the desired terminal position $x(1) = 0.2818$ within the time interval $0 \leq t \leq 1$ as illustrated in Figure 5. The aim is to find an optimal state trajectory and a control input defined as $x(t)$ and $u(t)$ respectively. The relation between them is made as

$$u(t) = \dot{x}(t) + x(t).$$

In which an accurate terminal position tracking is reached, the motion stays smooth to avoid vibrations and minimized the control effort. The cost of the control system is determine using the following quadratic cost functional

$$J = \frac{1}{2}\int_0^1 u^2(t) + x^2(t)dt.$$

The cost value J defines the balancing of energy consumption with deviation from the desired position. This formulation is widely used in optimal control problems of robotic manipulators to ensure efficient and precise motion while extending the operational lifespan of mechanical components.

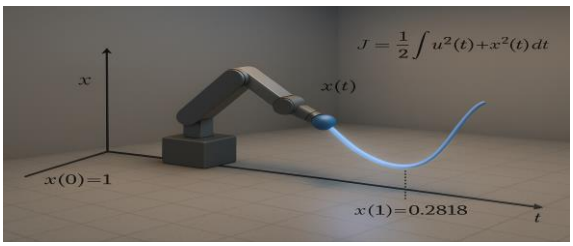


Figure 5: Illustration of robotic arm motion.

5.2 Robotic Arm Control Code in Python

```
import numpy as np
import matplotlib.pyplot as plt
# ====================================
# 1) Constants
# ====================================
sqrt2 = np.sqrt(2)
# Constant A from exact formula
A = (2*sqrt2 - 3) / (-np.exp(2*sqrt2) + 2*sqrt2 - 3)
# ====================================
# 2) Exact analytical solutions
# ====================================
def x_exact(t):
 return A*np.exp(sqrt2*t) + (1 - A)*np.exp(-sqrt2*t)
def u_exact(t):
 return A*(sqrt2 + 1)*np.exp(sqrt2*t) - (1 - A)*(sqrt2 -
1)*np.exp(-sqrt2*t)
# ====================================
# 3) Time grid
# ====================================
t = np.linspace(0.0, 1.0, 11)
# ====================================
# 4) Direct evaluation
# ====================================
x = x_exact(t)
u = u_exact(t)
# ====================================
# 5) Boundary condition check
# ====================================
print("x(0) =", format(x_exact(0.0), ".10f"))
print("x(1) =", format(x_exact(1.0), ".10f"))
# ====================================
# 6) Table of values
# ====================================
print("\n t x(t) u(t)")
print("-----------------------------------")
for ti, xi, ui in zip(t, x, u):
 print(f"{ti:3.1f} {xi:.10f} {ui:.10f}")
# ====================================
# 7) Cost functional J (numerical integration only)
# ====================================
J = 0.5 * np.trapz(u**2 + x**2, t)
print("\nJ_exact =", format(J, ".15f"))
# ====================================
# 8) Plot
# ====================================
plt.figure(figsize=(8,4))
plt.plot(t, x, 'o-', label='x(t)')
plt.plot(t, u, 's-', label='u(t)')
plt.xlabel('t')
plt.ylabel('Value')
plt.grid(True)
plt.legend()
plt.show().
```

5.3 Numerical Results for Robotic Arm Control

To solve this problem, the MSIVP method of order six is employed to approximate the state variable as

$$x_6(t) = \sum_{i=1}^{6} a_i 2^{(i-1)s}(z)^{i-1},$$

where s=1$s = 1$ and $T = 1$. The unknown coefficients are determined by solving a nonlinear programming problem subject to the boundary conditions. The optimal parameter vector is obtained as:

$$a_1 = 1,$$
$$a_2 = -0.692898043157134,$$
$$a_3 = 0.249438742839363,$$
$$a_4 = -0.056389173902395,$$
$$a_5 = 0.008969735170030,$$
$$a_6 = -0.000705039267015.$$

Substituting these coefficients yields the approximate state and control functions

$$x(t) = -0.0226t^5 + 0.1435t^4 - 0.4511t^3 + 0.9978t^2 - 1.3858t + 1.$$
$$u(t) = -0.0226t^5 + 0.0307t^4 + 0.1229t^3 - 0.3556t^2 + 0.6097t - 0.3858.$$

with an optimal cost value of $J = 0.192909335341236$.

In addition, the problem is solved using higher approximation orders through an extended incomplete series representation. The numerical accuracy is evaluated using the L_2 norm and theL_∞ norm for both the state and control variables over the interval $t \in [0,1]$. The corresponding error values are summarized in Tables 5 and 6, while the approximate solutions for different values of n are illustrated in Figures 6 and 7 while Figure 8 Statistical Reading of cost Functional Error.

Table 5: Errors for state of robotic arm problem.

n	x(t)	
	L_2	Infinity norm
6	6.48474317e-4	1.43087492e-4
7	6.46349909e-4	1.44111405e-4
8	6.46349909e-4	1.44160392e-4

Table 6: Errors for control of robotic arm problem.

n	u(t)*10^{-4}		J
	L_2	Infinity norm	E
6	2.744482616	5.69549097	8.642e-10
7	2.697338464	4.31755836	2.539e-12
8	2.710904281	4.39874067	7.993e-15

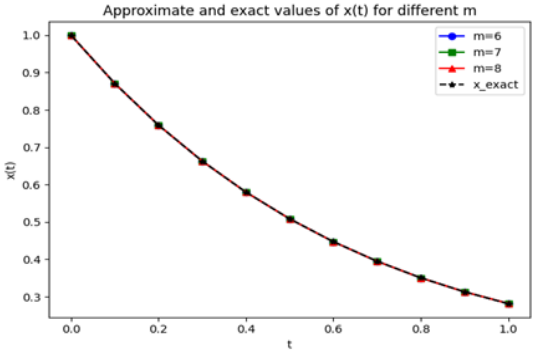


Figure 6: Approximate for state of robotic arm problem.

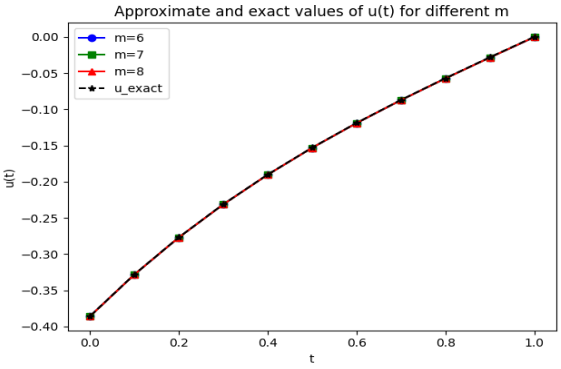


Figure 7: Approximate for control of robotic arm problem.

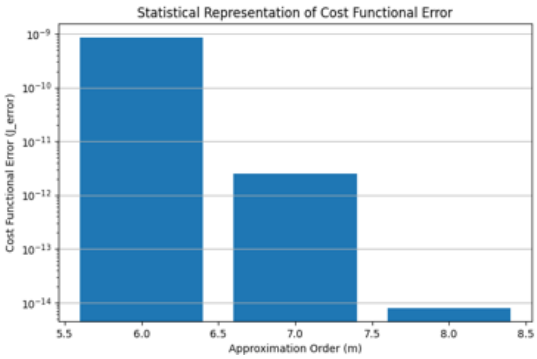


Figure 8: Statistical reading of cost functional error of robotic arm problem.

The simulation results show that the MSIVP method produces smooth and accurate trajectories for both the state and control signals. Error analysis indicates that the deviations in the state and control remain small throughout the entire time interval, confirming the effectiveness and numerical stability of the method.

6 CONCLUSIONS

This paper introduced an efficient computational approach based on modified shifted incomplete Vieta-Pell polynomials for solving optimal control problems over general time intervals. The proposed method transforms the original control problem into a numerically manageable optimization problem through simple and effective operational matrices. From an information technology standpoint, the MSIVP algorithm provides a flexible and computationally efficient tool suitable for implementation in software-based control systems, intelligent robotic platforms, and digital automation frameworks. Numerical results demonstrate fast convergence, high accuracy, and reduced computational effort, making the method appropriate for real-time and simulation-based IT applications. The effectiveness of the proposed method is further validated through robotic motion control examples, confirming its applicability to intelligent systems and IT-driven control environments. Future work may focus on real-time implementation and integration with advanced robotic software architectures.

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SECTION 5

STATISTICAL MODELLING AND ANALYSIS AND THEIR APPLICATIONS IN LIFE SCIENCES

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Lung Disease Detection by Processing X-ray Image Database Using Deep Learning Techniques

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Keywords: Chest X-Ray Images, Classifications, InceptionV3, Medical Imaging, Database.

Abstract: Integrating technology such as artificial intelligence in the medical field may contribute significantly to the early diagnosis of diseases. This study is conducted to achieve two goals: The first is to use three advanced deep learning models to identify tuberculosis and COVID-19 diseases from healthy cases by processing a chest X-ray image dataset. The second goal is to compare the three models and identify the most generalizable one based on accuracy and computational efficiency. The proposed models were applied to a large-scale chest X-ray of 6375 images. The findings show that InceptionV3 outperforms the CNNs and ResNet-50 algorithms by achieving high metrics values (Accuracy = 0.9636, Precision = 0.9752, Recall = 0.9554, and F1-Score = 0.9651). Furthermore, the results show that training neural networks across a wide range of epochs improves the model predictions of new data. The findings demonstrate InceptionV3's capability of providing a robust and automated method for classifying chest X-ray images. Apart from accuracy assessment, this computational analysis depicted marked variations in efficiency amongst the three models. The CNN architecture achieved the shortest training time of ≈12.4 minutes and attained the fastest inference speed of ≈4.1 ms per image, whereas ResNet-50 and InceptionV3 required longer training and inference times. This starkly indicates that there is a clear trade-off between computational cost and predictive performance across the evaluated architectures.

1 INTRODUCTION

Chest X-rays are a primary tool for symptomatic imaging that provide essential insights into the syndrome of thoracic depression [1].
Furthermore, Chest X-rays can provide important information about some diseases, such as COVID-19 and tuberculosis (see Fig.1).

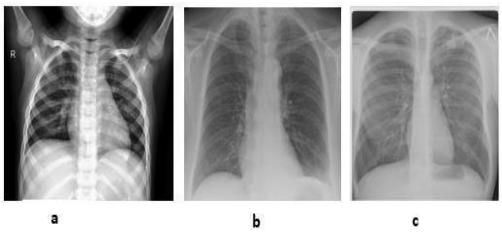


Figure 1: Three conditions of Chest X-ray images: a) Normal, b) COVID-19 and c) Tuberculosis.

Therefore, precisely and effectively interpreting these images is crucial for diagnosing, treating, and controlling several cardiovascular disorders. Historically, this job has necessitated the advanced knowledge of experienced radiologists, a proficiency sometimes constrained by workload and geological irregularities[2].

Recent advancements in utilizing artificial intelligence techniques have emerged as a valuable tool in transforming the analysis of medical images. These models can enhance the capacities of radiologists, contributing to improvements in symptomatic accuracy and competence [3]. Therefore, efforts are ongoing to improve the quality of medical care by researching new algorithms and solutions to apply them in the medical field [4]. New techniques such as deep learning algorithms have attracted significant attention in many medical studies, especially pulmonary diseases. For example, the study of Nayak et al. [5] presented an automated early diagnosis system by processing X-ray images utilizing deep learning models. In their study, eight pre-trained CNNs models were investigated to

classify COVID-19 from healthy cases. The best model, ResNet-34, provided an accuracy of 98.33% on the tested chest X-ray images. The study of Singh et al. [6] used a CNNs algorithm to identify COVID-19 in chest X-ray images. The CNNs and VGG16 models were pretrained on the image dataset and used transfer learning and image processing techniques to increase detection accuracy. The dataset consists of normal and COVID-19 chest X-ray images. The results show that the CNN model successfully extracts useful features from the small dataset, suggesting that image processing and deep learning could be used for early and precise diagnosis. The CNNs model has the potential for medical professionals to diagnose COVID-19 and could help create automated screening systems for the pandemic's eradication. The Author found that the VGG16 model reduces overfitting and enhances model performance, making it particularly useful for smaller datasets like COVID-19 chest X-ray images. Six artificial deep neural networks were utilized to identify COVID-19 from chest X-rays images [7]. A total of 2905 COVID-19, viral pneumonia, and healthy chest X-rays were included in that study. With an overall accuracy of 96.91%, ResNet-50 was the most successful network. The model showed a high performance in the loss of detection of COVID-19 cases, indicating that it is a faster and more accurate method of detection.

Machine learning, especially deep learning, has been extensively explored in the context of corona detection, and a classifier has been trained to obtain positive corona or determine negative corona X-ray images as shown in [8]. This paper utilized Apache Spark and Deep Transfer Learning methods to create a classifier for COVID-19 chest X-ray images, achieving 100% accuracy in COVID/Normal/pneumonia, with 97 percent accuracy for InceptionV3, ResNet50, and VGG19 models. The study conducted by Mujahid et al. [9] detected pneumonia from X-ray images with pre-trained convolutional neural networks (CNNs) such as VGG16, Inception-v3, and ResNet50. The results indicate that Inception-V3 with CNNs had the best recall and accuracy rates, at 99.73% and 99.29%, respectively.

The goal of this paper is to propose a prediction model based on CNN algorithm. Therefore, the proposed model was applied to Chest image dataset to identify COVID-19 and Tuberculosis from healthy ones. The performance of our proposed model was evaluated using accuracy, specificity, recall, and F1-score metrics.

2 MATERIAL AND THEORETICAL BACKGROUND

2.1 Model Architecture and Transfer Learning

Figure 2 presents the flowchart of the proposed methodology used in this study. Up to 6078 publicly available chest X-ray images were processed. The dataset is subdivided into normal, tuberculosis, and COVID-19 images. For preprocessing, the images are resized to 224 × 224 pixels. The images were subdivided into 3 groups: 60% training, 20% testing and 20% validation. The images were evaluated and classified using three proposed models of this study.

CNNs are widely used in medical imaging, such as image recognition and chest X-ray classification, due to their ability to learn spatial hierarchy and detect abnormalities with high accuracy. CNNs include an input layer, an output layer, and several hidden layers that learn new and complex objects and patterns. Convolution and pooling operations are then applied to a subsample of the provided input, which is then passed through an activation function.

In contrast, InceptionV3 is a CNN-based model and potentially a fundamental depth learning that is commonly used in various exploratory considerations for image classification tasks [8]. InceptionV3's victory lies in its architecture's capability to extricate complex features from pictures. It is a profitable tool for precise classification tasks in areas like mechanical apparatus support, medical diagnostics, and ecological observation [10].

In addition, ResNet-50 is a deep CNN architecture that is broadly utilized in different areas, including therapeutic picture investigation and plant illness discovery [11]. Moreover, ResNet-50 has been investigated for assessing optical properties in scrambling media, displaying comparable or way better-remaking precision with training on smaller datasets and potential for assist improvements [12].

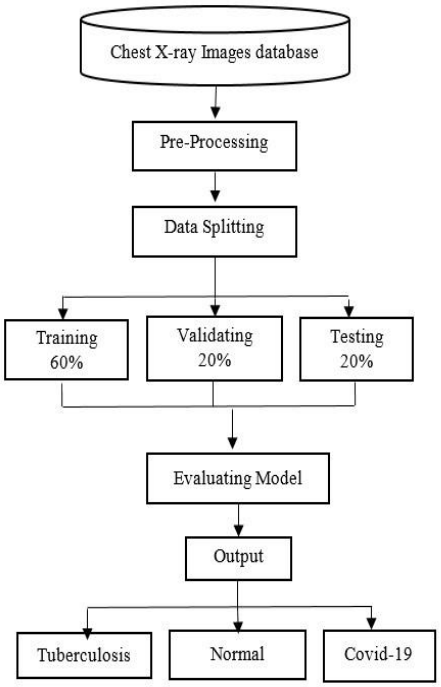


Figure 2: Flowchart of the proposed methodology.

The three models presented above achieved significant success in many computer vision tasks and have been adapted for the diagnostic analysis of medical images with promising results [13]. ResNet-50 has demonstrated exceptional performance in image classification tasks by addressing the paradox of the vanishing gradient problem[14]. In contrast, InceptionV3 employs a multi-scale preparation method, effectively capturing visual features at various degrees of reflection [15]. Therefore, this work investigates the suitability of three modern algorithms, CNNs, ResNet-50, and InceptionV3, for identifying tuberculosis and COVID-19 diseases from healthy cases by processing a chest X-ray image dataset. The study also aims to compare the three deep-learning architectures to determine which model provides the best balance of accuracy, generalization capability, and computational cost.

2.2 Data Splitting

The data is divided into training, validation, and testing sets, as shown in Table 1.

Table 1: Data splitting.

Class	Training	Validating	Testing	Total
Normal	1207	402	404	2013
Covid-19	1218	406	704	2328
Tuberculosis	1220	406	408	2034

2.2.1 Adjusting the Size of Image

All the used images of this study were resized to 224×224 pixels to be compatible with the requirement of deep learning models. This step enhances the process of extracting and selecting features.

2.2.2 Converting Image to Grayscale

The X-ray images were transformed into grayscale to emphasize details of structure essential for evaluation, thus minimizing the computational effort and removing unnecessary color data irrelevant to the purpose.

2.2.3 Normalization

Each pixel was normalized to the pixel intensity values range of [0, 1]. This step increases mode training performance.

2.2.4 Noise Reduction

In this study, the quality of images was improved by reducing noise and artifacts through using median filter.

2.2.5 Contrast Adjustment

To improve the contrast of the images and accessing the small details such as changes in lung visibility, histogram equalization was applied.

2.2.6 Dataset Balancing

Class imbalance was assessed in the dataset, especially where one group (like COVID-19) can predominate over others. To guarantee an equal representation of all classes, synthetic oversampling

methods like SMOTE (Synthetic Minority Over-Sampling Technique) were investigated. An example of pre-processed lung image is shown in Figure 3, which presents the enhancements steps that applied to the images.



Figure 3: Example of image pre-processing step.

2.3 System Evaluation

The performance of a model is explained by evaluation metrics. Evaluation metrics are evaluated based on their ability to distinguish between model outcomes [16]. The classification process gives four conceivable results: false negative, true negative, true positive, and false positive. Accuracy, recall, F1 score, and precision are utilized as execution evaluation measurements in this consideration [17].

2.4 Model Architectures and Hyperparameters

This section discusses the three model's parameters and setting in this project. First model is (CNN):

- Structure: Three consecutive Convolution layers with 32, 64, and 128 filters (kernel size = 3x3) and a 2x2 MaxPooling after each layer.
- Flatten the layer, then create a Fully Connected layer with a size of 512 neurons and a Dropout of 0.5.
- An output layer with three nodes (softmax) for three categories (Normal, COVID-19, Tuberculosis).
- Training Parameters: Image size: 224x224, Batch size = 32, Optimizer: Adam, Learning rate: 0.001, Number of epochs (up to 50 as in experiments).
- This model represents a lighter and simpler baseline, providing a comparison with deep models (ResNet, Inception).

The second model is (InceptionV3):

- Structure: Use InceptionV3 pre-trained on ImageNet with `include_top = False`.
- Additions: `GlobalAveragePooling2D`, A 1024-sized Dense layer with ReLU, A 3-node softmax output layer, Freeze the base InceptionV3 layers during training (only the top layers are trained).
- Training Parameters: Image size 224×224, batch size = 32, `optimizer = Adam, loss = categorical_crossentropy`
- InceptionV3 is known for its ability to capture multi-scale features, making it suitable for detecting subtle lung patterns in X-rays.
- Using transfer learning reduces the need for large datasets and leverages the general features derived from ImageNet.

The third model (ResNet-50):

- Structure: Use pre-trained ResNet-50 with include_top = False`.
- Additions: `GlobalAveragePooling2D`, `Dense 1024 with ReLU`, `Dense 3 with softmax`.
- Freeze the base ResNet layers (fine-tuning only for the top layers).
- Training Parameters: Image size 224×224, batch size = 32, Rescale images like Inception V3, `optimizer = Adam, loss = categorical_crossentropy`.
- Number of epochs (in the paper, ensure the number is consistent with what you actually implemented).
- ResNet-50 uses residual connections to address the vanishing gradient problem and allows for learning deep and accurate representations.
- It is a suitable middle ground between a simple CNN and Inception in terms of complexity and representational power.

3 RESULTS AND DISCUSSION

The proposed algorithms were used to explore the accuracy of diagnosing tuberculosis and COVID19 from the chest X-ray images. Table 2 contains the accuracy results of the proposed algorithms. The Inception-V3 model showed the highest accuracy when compared to the other models. Inception-V3 demonstrated effective performance in identifying X-ray images, with an accuracy of 0.9631, precision of 0.9752, recall of 0.9554, and an F1-score of 0.9651.

Table 2: Results of fine-tuned pre-trained models.

Model	Accuracy	Precision	Recall	F1-Score
CNNs	0.8613	0.8821	0.8116	0.8453
ResNet50	0.8975	0.9168	0.8963	0.9064
InceptionV3	**0.**9631	0.9752	0.9554	0.9651

Figure 4 presents the Accuracy results of the proposed algorithms versus epoch number. One can observe from Figure 4a, the validating and training accuracy of the ResNet50 model through 50 epochs. We notice that the highest precision is 89.75%. Figure 4.b shows the training and validation curves for Inception-V3.

The model reaches a training accuracy of 96.31%, and the validation accuracy remains consistently high across epochs, indicating stable learning behavior. All of the models are trained, approved and tested for normal, COVID-19, and Tuberculosis classes. Figure 4c shows the training and validation of the CNN model. We see that the accuracy is 86.13%. For 50 epochs, three models were trained on 3 classes, stability and performance enhancement registered in these models tune.

According to these curves, all models exhibit strong performance on both the training and validation datasets, achieving high levels of accuracy. The Inception-V3 shows (Fig. 4b) superior execution of the validation information with a precision of around 96%, making it the finest choice among the three models.

When using long periods of up to 50 epochs to train and test the data, we noticed that the results started to stabilize with little change after period 20. The same fluctuations appeared for the data during the training period, and the same thing was observed for the data's results during the test period.

The computational performance (training and inference time) for the three models shown in Table 3.

Table 3: Training and inference time in minutes.

Model	Training time	Inference time
CNNs	12.4	4.1
ResNet50	45.8	9.8
InceptionV3	59.6	16.3

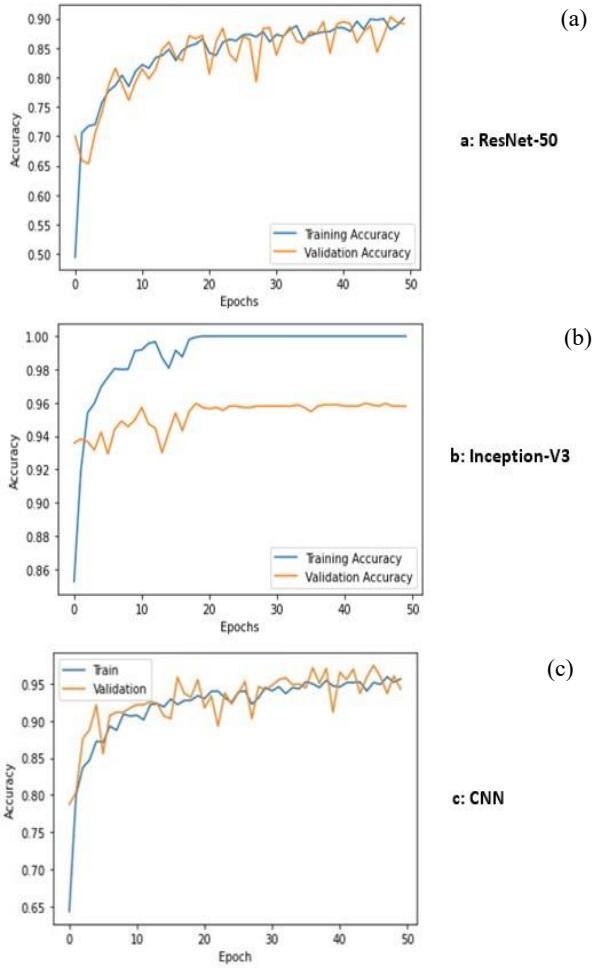
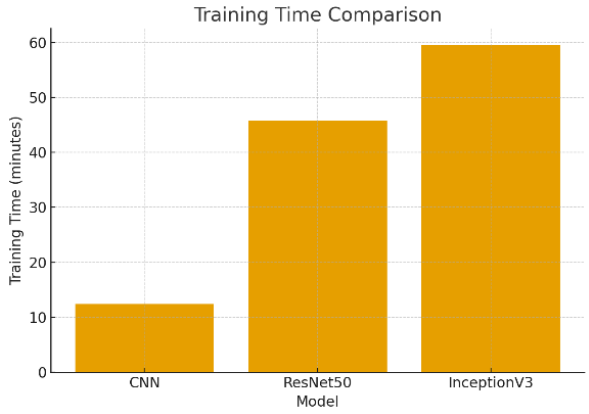


Figure 4: Accuracy results of the proposed algorithms: a) ResNet-50, b) Inception, c) CNN.

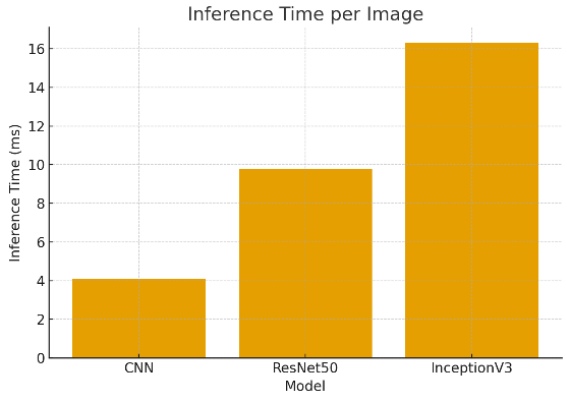
The computational analysis showed that the CNN model required the shortest training time (≈12.4 minutes), followed by ResNet-50 (≈45.8 minutes), while InceptionV3 needed the longest time (≈59.6 minutes) due to its deeper architecture.

For inference, CNN achieved the fastest prediction time per image (≈4.1 ms), whereas ResNet-50 and InceptionV3 required ≈9.8 ms and ≈16.3 ms respectively.

The bar chart in Figure 5 clearly demonstrates the computational cost across the three models.



(a)



(b)

Figure 5: Proposed algorithms (ResNet-50, Inception, and CNN): a) Training time, b) Inference time.

4 CONCLUSIONS

Experimental results demonstrated the efficiency of the proposed system in achieving robust classification performance. Even though the models produced encouraging results, a further comparative analysis revealed that Inception-V3 had the best overall performance and the highest accuracy. This makes it reasonable for simple applications where high accuracy is essential, as therapeutic symptoms, and is particularly persuasive for this classification assignment. Inception V3 offers the highest accuracy and F1 score.

Therefore, it is medically the best choice for the early detection of COVID-19 and tuberculosis.

Measuring the results of training and inference time, CNN is the fastest in training and inference, but the least accurate. ResNet-50 strikes a balance between accuracy and time. Inception V3 is the most accurate but the slowest in training and inference.

In conclusion, Inception V3 is suitable for systems where accuracy is a priority (such as central hospitals). CNN is suitable for systems requiring high speed (triage systems). ResNet-50 is a good compromise for applications with moderate resources. The importance of careful model selection and hyperparameter tuning for optimal performance in medical image investigation assignments has been highlighted by these findings. The effective implementation of deep learning in chest X-ray classification may enhance clinical treatment by increasing radiologists' proficiency and facilitating the identification of prior infection sites. Future studies should focus on helping to advance model execution, addressing issues like imbalanced datasets and clarifying capacity, and exploring how these models can be integrated into clinical workflows. The ultimate goal is to develop AI-based tools to improve patient care and advance diagnostic accuracy.

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Towards Intelligent Care: Human Behavior Analysis Using Energy Consumption and Door Operation Patterns in the Internet of Care Things

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Keywords: Human Behavior Analysis, Unsupervised Learning, Clustering, Pearson Correlation, Environmental Sensors, Internet-of-Care-Things (IoCT), Intelligent Algorithm, Anomaly Detection.

Abstract: The analysis of human behavior is an interdisciplinary science aimed at recognizing, describing, and predicting patterns of human behavior and emotional states. With the development of sensor technologies and data-driven approaches, new opportunities have emerged for observing and modeling everyday human activity. This study is based on a real-world dataset collected over one month from five participants in a residential environment. The data were gathered using environmental sensors, specifically contact sensors and energy consumption sensors, which enabled monitoring of user interactions with their surroundings. A set of statistical and machine learning methods was applied, including K-means clustering, correlation analysis, time-series representation, calculation of mean values, and aggregation of correlations. The results show how contact sensors and energy consumption sensors are related, how daily load is distributed, how periodic the data are, which sensors behave in a similar way within groups and across the system, and how individual behavioral models of each user can be formed. These findings highlight the potential of sensor-based analysis for advancing behavioral research and its practical applications.

1 INTRODUCTION

The risk of social isolation in private living has been shown to increase with age. Modern approaches in the fields of automation and health sciences can reduce this risk by enhancing social and psychological resilience in older adults [1].

In the context of demographic change, the associated increase in demand for care services and shortage of nursing staff present the healthcare system with urgent challenges that require immediate attention. Digital assistive technologies could be the solution to this problem [2].

In the PräEinsamAltKI project, researchers are using innovative digital solutions to prevent loneliness: a system is being developed for a model apartment that enable automatically and at an early stage identify increasing isolation in older people. It is expected to consist of a sensor network based on Internet of Care Things (IoCT) technologies and artificial intelligence (AI) capable of identifying signs of social isolation[1].

The subjects of the study are five users. The object of the study is individual daily electricity consumption indicators, as well as the total number of door and window openings available to all users.

One of the research tasks within the project is to analyze user behavior patterns, explore relationships between sensor measurements, and evaluate the informational value of the collected data. Accordingly, this article investigates behavioral trends in residential environments using electricity consumption data and door and window opening events, examines whether a measurable relationship exists between these two sensor modalities, and evaluates the extent to which such multimodal data can provide meaningful insights that may support the early detection of changes potentially related to social isolation.

[1] https://www.hs-anhalt.de/praeeinsamaltki/uebersicht.html

2 METHODOLOGY

To address the research task, a dataset was constructed, an analysis plan defined, data processing was performed, and the result subsequently interpreted.

Common approaches include wearable sensors (accelerometers, heart rate monitors, biosensors), environmental sensors (cameras, Wi-Fi), mobile devices and self-report surveys or diaries for subjective input are used for data collecting [3], [4].

Once collected, data can be processed using methods like computer vision for video-based action recognition, or machine learning and deep learning models that extract patterns from multimodal signals. Researchers use both knowledge-driven approaches (e.g., social force models) and data-driven methods (e.g., RNNs, GCNs, GANs, reinforcement learning), with hybrid techniques combining domain expertise and AI gaining popularity [4], [5].

Energy consumption readings are processed using a time series database. As ordinary regression methods are not suitable for predicting these data, advanced algorithms such as RNN-LSTM, ARIMA, and others are applied [6].

In contrast to these technologically advanced and computationally intensive approaches, this study primarily employs statistical analysis and environmental sensor data. The analytical tools include descriptive statistics, clustering, correlation analysis, and time-dependent visualizations.

2.1 Dataset

The dataset was constructed from real sensor readings collected over one month. It consists of an array of timestamps corresponding to sensor states, each linked to specific entities.

It includes the electricity consumption data from smart plugs throughout the day for each of the five users. The contact sensor data represent the number of window or door openings per day. State values are represented in numerical format. Non-numeric observations (e.g., unavailable or NaN) were converted to zero values. The absence of data was interpreted as non-use.

The corresponding number of rows for each entity is presented in Table 1.

Thus, each entity is represented by the corresponding set of dimensions for the analyzed period.

2.2 Data Analysis Procedure

In the initial stage, the data for the entire period were visualized as time series to identify general patterns [7].

Next, mean and maximum values for each sensor were calculated by day of the week, based on which a summary table of average daily indicators was created [8]. The obtained aggregated values were used to perform unsupervised learning cluster analysis using the k-means method [9].

Additionally, heatmaps were constructed based on the average energy consumption throughout the day, which allowed to determine the load distribution pattern and the outlet usage hours.

In the next stage, the data was divided into three-time intervals, after which the Pearson correlation coefficients were calculated for each pair of features [10], [11]. The results of the correlation analysis were visualized as correlation matrices. Based on these matrices, the number of strong and moderate positive and negative correlation coefficients were calculated for each entity, indicating the prevailing direction of relationships between the sensors.

3 RESULTS

This section presents a step-by-step analysis of the procedures described in section 2.2.

The data visualization presented in Figures 1 and Figure 2 demonstrates the presence of patterns in the sensor readings. It is observed that the highest values persist for 4-5 days followed by a decrease. Five groups of peak values can be identified, indicating the periodic use of the sensors.

Thus, user behavior can be characterized as periodic, which is confirmed by the analysis of both graphs. As the individual consumption of each energy sensor increases the contact values also rise.

The average value calculated for the maximum value by day of the week for each sensor is presented in Table 1.

The maximum energy consumptions for each user occur on weekdays and the same trend is observed for contact sensors as well. For example, both are either minimal or absent on weekends.

Based on the window sensor data, the room is ventilated approximately once per day on weekdays.

From the table, it can be assumed that either the users connect different devices to their sockets or the usage times differ.

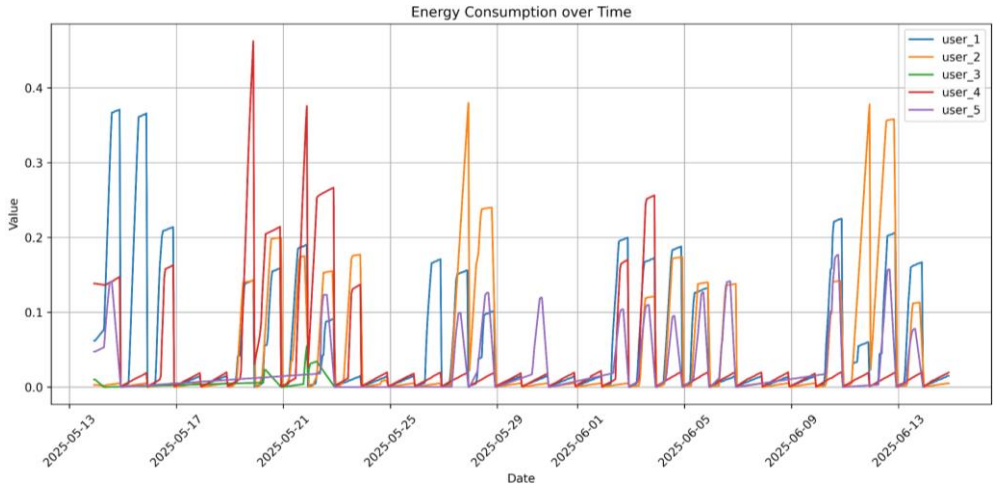


Figure 1: Time series of energy consumption sensors.

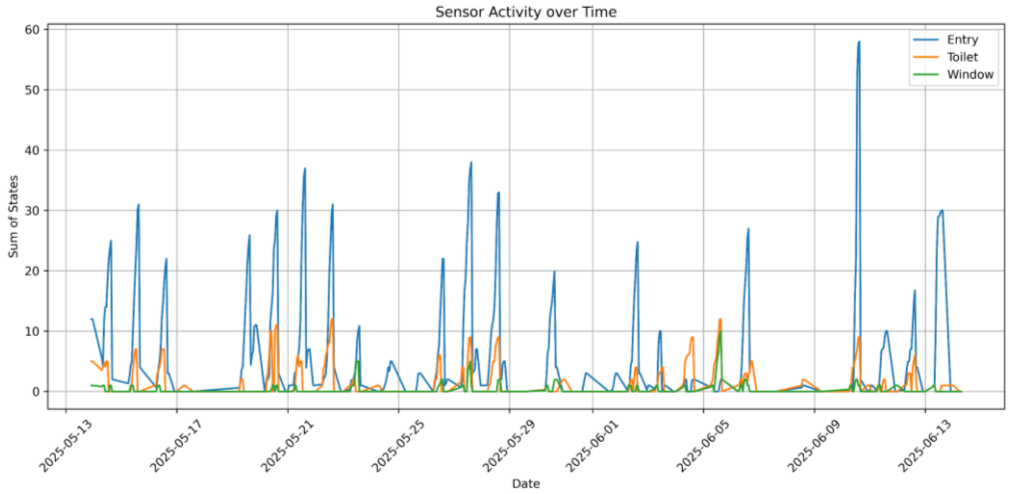


Figure 2: Time series of contact sensor values.

Table 1: Number of rows for each entity in dataset.

Energy sensors					
	user1	user2	user3	user4	user5
Rows	761	461	24	761	156
Contact sensors					
	entry		window		toilet
Rows	367		139		236

Table 2: Mean value for every sensor by day of week.

Entity	M	Tu	W	Th	Fr	Sat	Sun
user1, kW	0.132	0.155	0.198	0.162	0.085	0.014	0.014
user2, kW	0.039	0.169	0.162	0.132	0.087	0.005	0.005
user3, kW	0	0.016	0.018	0.034	0	0	0
user4, kW	0.167	0.129	0.097	0.068	0.071	0.019	0.019
user5, kW	0.104	0.108	0.107	0.135	0.113	0	0
entry	10.3	11.9	7.5	6.4	10.2	1.1	1.8
toilet	3.0	3.5	2.9	3.4	1.8	0.5	2.0
window	1.3	1.2	1.0	2.0	1.3	0.0	0

Clustering was performed to group data based on statistical features. To determine the number of clusters, the elbow method was used, which indicated that the optimal number of clusters for both groups is two.

As a result, it can be seen in Figure 3 that the behavior of the entry door differs significantly from their behavior on weekends and from that of all other contact sensors on other days. As already mentioned, the behavior of this sensor can be divided into weekday and weekend patterns. For all others, no other clearly visible useful information can be obtained. Despite the fact, that all other doors are used a far less times.

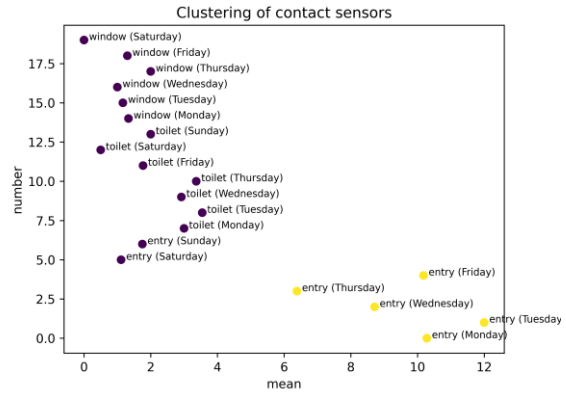


Figure 3: Clustering K-Means for contact sensor values.

The diagram obtained for the energy consumption sensors in Figure 4 appears more dispersed.

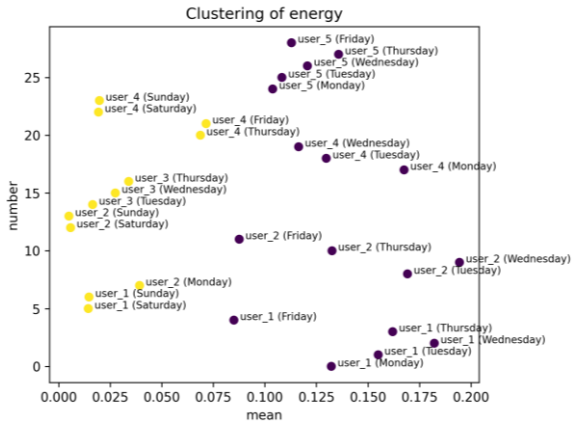


Figure 4: Clustering K-Means for energy sensor values.

User 3 stands out in that their consumption consistently remains at a low level, comparable to the weekend consumption of other users. User 5, on the contrary, is always part of the high-consumption group. The behavior of Users 1, 2, and 4 varies depending on the day of the week, showing a tendency toward higher consumption on most weekdays, which explains their assignment to both groups.

A clear periodic consumption is observed: activity on weekdays (purple group) is significantly higher than on weekends (yellow group). Thus, it can be concluded that the consumption is periodic, with higher levels during weekdays.

How does the situation develop within the weekdays themselves? The evolution if consumption patterns across weekdays is further examined through the heatmap presented in Figure 5.

In this diagram, the dark blue indicates 100% of the maximum value for each entity, while lighter shades correspond to lower levels of consumption. A striking feature of the visualization is the presence of empty cells during Saturday and Sunday. For several users, the values are either missing or remain extremely low, in many cases approaching or reaching zero.

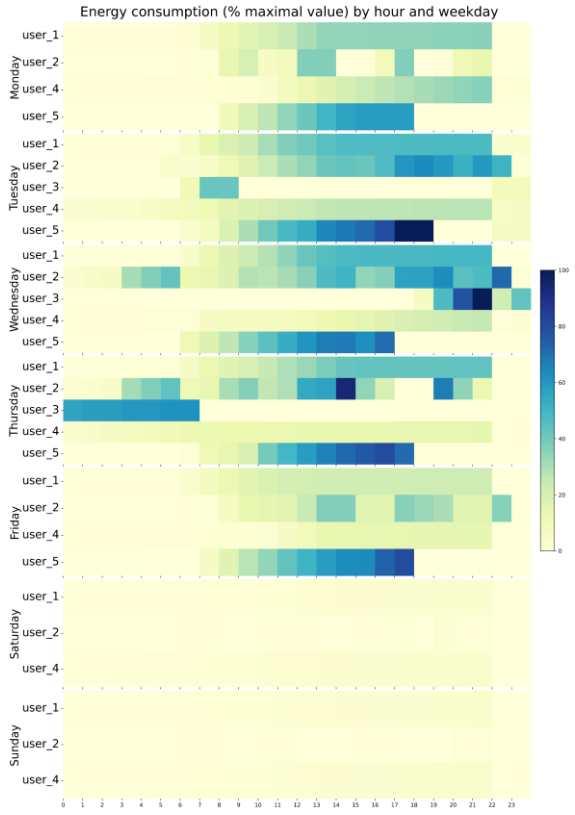


Figure 5: Hourly heatmap of consumption values expressed as a percentage of the maximum per user.

It is also evident that for many users, values gradually increase throughout the day. For example,

User 1 uses it's socket from Monday to Thursday between 8 - 9 a.m. and 2 - 3 p.m., after which energy consumption stops increasing and remains stable.

User 2, in turn, uses the socket consistently from Monday to Friday. On Monday and Thursday breaks in usage are observed. Often, usage starts at 8 a.m. and continues until 3 p.m., although values are occasionally recorded in the early morning.

User 3's consumption values are logged either before 9 a.m. or after 6 p.m. Which is compared to other users can be described as abnormal.

User 4's consumption pattern is less distinct, with activity sometimes beginning at 9 a.m. and other times at 12 p.m., and ending at 3 p.m. or 10 p.m., respectively.

User 5 exhibits a more stable pattern: from Monday to Friday, the socket is used consistently between 9 - 10 a.m. and 5 - 6 p.m.

The presented values indicate that the sockets are not in use continuously throughout the day. To analyze how the individual sensors relate to one another, Pearson correlation is employed.

In the correlation heatmaps, green denotes a positive relationship, meaning that the corresponding sensors tend to increase simultaneously. Conversely, colors shifting toward red reflect a negative relationship, where an increase in one sensor is associated with a decrease in another.

Figures 6 - 12 display these correlations across all days of the week, differentiated by three distinct time periods, thereby providing a detailed view of temporal variations in sensor relationships.

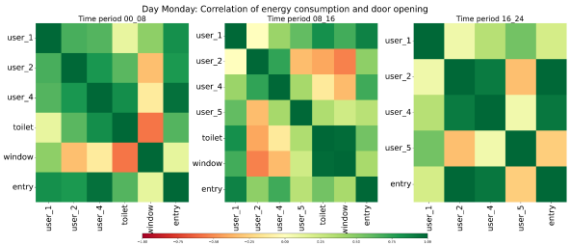


Figure 6: Pearson correlation of sensor values on Monday.

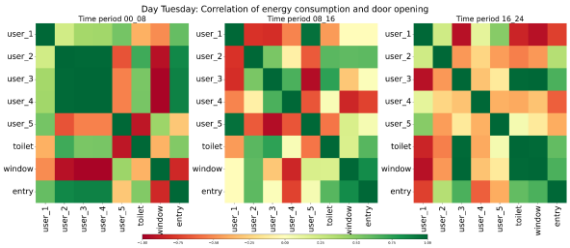


Figure 7: Pearson correlation of sensor values on Tuesday.

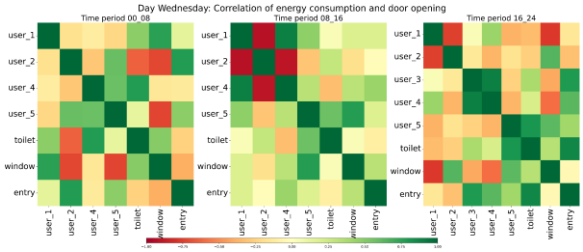


Figure 8: Pearson correlation of sensor values on Wednesday.

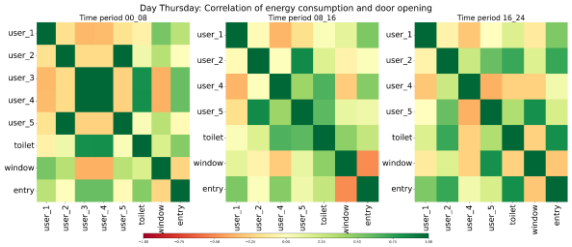


Figure 9: Pearson correlation of sensor values on Thursday.

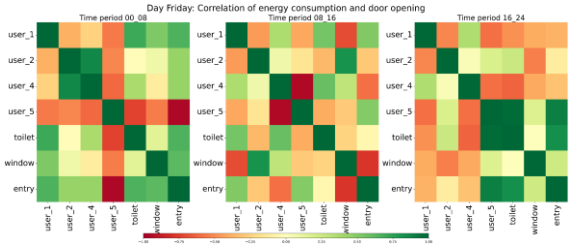


Figure 10: Pearson correlation of sensor values on Friday.

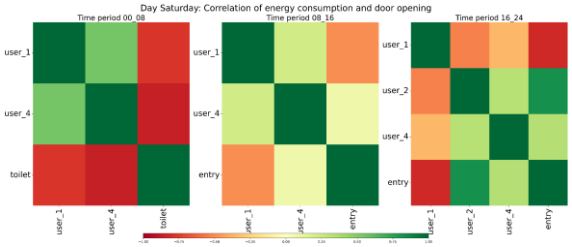


Figure 11: Pearson correlation of sensor values on Saturday.

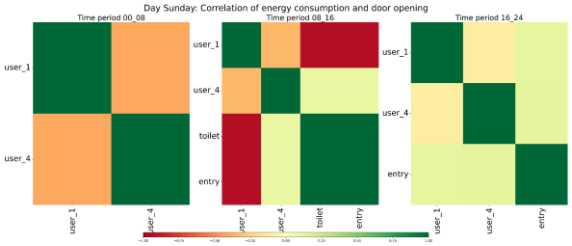


Figure 12: Pearson correlation of sensor values on Sunday.

Given the large number of correlations, a summary was created to facilitate interpretation. The average and strong correlations between entities across all periods were compiled and are presented as a bar diagram in Figure 13.

The analysis of correlations reveals distinct interaction patterns among the users and environmental sensors across different time periods (morning, daytime, and evening).

User 1 exhibits predominantly negative correlations with Users 2 and User 3 during both daytime and evening hours. In contrast, correlations with Users 4 and 5 are consistently positive across all time periods. In terms of contact sensors, correlations with all doors and the windows tend to be negative in the evening and positive in the morning. During daytime, positive and negative correlations are balanced, except for the entry door, where positive correlations are stronger.

The correlation between Users 2 and User 3 are positive at night and during the day, but becomes negative in the evening. For User 4, correlations tend to be positive during the evening and nighttime, whereas for User 5, positive and negative correlations occur with approximately equal frequency. A similar balance is observed for User 4 during daytime hours. Correlation between User 2 and the entry door remains consistently positive throughout all time periods. For the window, positive correlations dominate during the day. Correlations involving the toilet door are generally mixed, with the exception of nighttime hours, during which positive correlations predominate.

User 3 exhibits predominantly positive correlations with User 4 across all time periods, particularly at night. In contrast, correlations with User 5 are generally negative, except during the evening, when no correlation is observed. Regarding the entry door, correlations are positive in the morning and evening but absent during daytime hours. For the toilet door, correlations remain consistently positive across all periods, whereas correlations with the window are positive in the morning and neutral in the evening.

Between Users 4 and User 5, correlations are predominantly negative across all time periods. With the entry door, correlations remain consistently positive. With the toilet door, correlations are positive in the morning and during the day. In contrast, correlations with the window are consistently negative across all time periods.

Correlations between User 5 and both the entry door and the window are positive during daytime and evening hours. Correlations involving the toilet door are mixed during daytime hours but become predominantly positive in the evening.

4 CONCLUSIONS

The conducted analysis demonstrates that user behavior exhibits a clear periodic structure, with significantly higher activity levels and sensor usage during weekdays, followed by a sharp decrease or complete absence of activity on weekends. This pattern is consistent across both energy consumption and contact sensors, confirming that users tend to follow stable daily routines strongly linked to the working days.

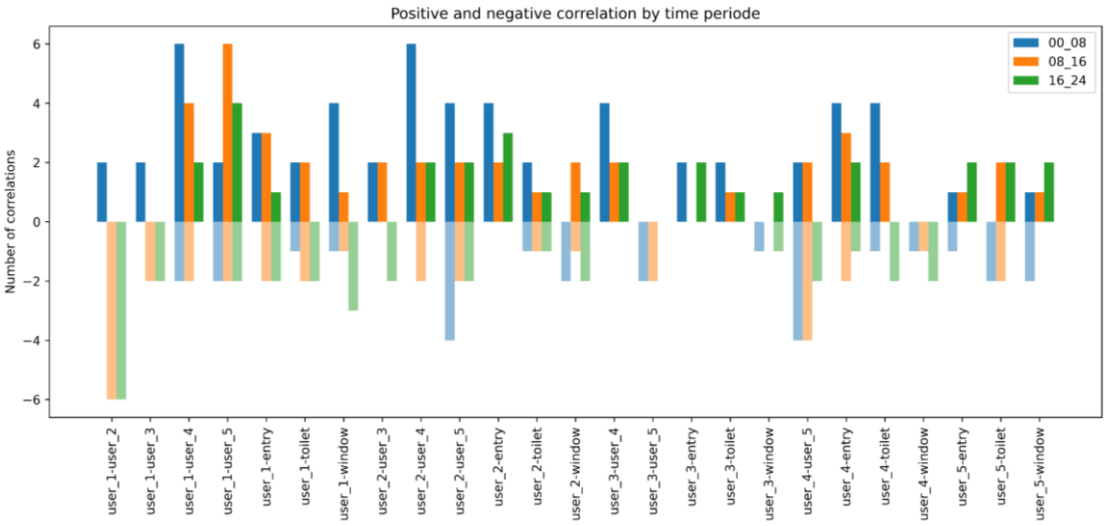


Figure 13: Positive and negative correlation by period.

Clustering analysis revealed that users can be divided into distinct groups: some consistently show higher energy consumption (e.g., User 5), while others remain at low levels (e.g., User 3), independent of the day of the week. Users 1, 2, and 4 display more variable behavior, with their consumption fluctuating depending on the weekday, yet still showing a tendency toward greater usage on working days.

The hourly heatmap analysis further confirmed these patterns by highlighting that sockets are not in continuous use but rather concentrated in specific periods, typically between morning and late afternoon. This reflects daily working rhythms and indicates that user activity is temporally bounded and highly structured.

Correlation analysis revealed both synchrony and divergence in user behavior. While Users 1, 2, and 3 tend to avoid simultaneous usage, Users 4 and 5 demonstrate stronger positive correlations with others, suggesting complementary or overlapping usage patterns. Interactions with environmental sensors such as doors and windows also exhibit temporal dependence, showing predominantly positive correlations in the morning, balanced dynamics during the day, and negative correlations in the evening.

Overall, the study demonstrates that even simple, low-cost, and non-intrusive sensors - such as energy consumption and contact sensors - can provide complementary and meaningful insights into user behavior in shared residential environments. Their combined use enables the identification of daily routines, user-specific patterns, and interaction dynamics between individuals and their environment, providing a transparent and interpretable baseline for future AI-driven systems. By establishing typical behavioral patterns for each user, this approach lays the foundation for detecting deviations that may signal changes in daily life, which could potentially support the early identification of situations associated with reduced engagement or emerging social isolation.

ACKNOWLEDGMENTS

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A Cross-Dataset Evaluation of Machine Learning Approaches for Autism Spectrum Disorder Across Age Groups

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Keywords: Autism Spectrum Disorder (ASD), Early Detection, Clinical Data, Machine Learning.

Abstract: Autism Spectrum Disorder (ASD) is a complex neurodevelopmental condition that requires timely and accurate detection for effective intervention. This study evaluates the performance of six machine learning models – Logistic Regression, Support Vector Machine (SVM), Decision Tree, Random Forest, XGBoost, and k-Nearest Neighbors (kNN) – in detecting ASD across three age groups, using three separate datasets: children, adolescents, and adults. Using a comprehensive dataset segmented by age, each model was assessed through stratified 10-fold cross-validation based on five key performance metrics: accuracy, precision, recall, F1 score, and area under the curve (AUC). The findings indicate that ensemble and linear models, particularly XGBoost and Logistic Regression, consistently deliver the most reliable results across all age groups and the combined dataset, with high classification accuracy and balanced precision-recall tradeoffs. In contrast, kNN and Decision Tree models displayed inconsistent performance, often struggling with both false positives and false negatives. This analysis supports the application of advanced machine learning methods, especially ensemble techniques, for developing robust and generalizable ASD detection systems across diverse age demographics.

1 INTRODUCTION

Autism Spectrum Disorder (ASD) is a neurodevelopmental condition that typically manifests within the first three years of life [1]. It is primarily characterized by challenges in social interaction, communication difficulties, restricted interests and repetitive behaviors [2]. Individuals with ASD often struggle to understand others' emotions and thoughts, which can make interpersonal communication difficult. According to the World Health Organization (WHO), approximately 1 in 270 people globally are affected by ASD [3]. Each individual spectrum presents a unique set of characteristics – while some face significant challenges, others may exhibit exceptional abilities in areas such as visual processing, academics or music. Early diagnosis and intervention are crucial in managing ASD effectively. Detecting ASD early enables more timely and targeted treatments, which can significantly improve outcomes and reduce the long-term impact of the disorder. Traditionally, symptoms are identified through clinical observation, which can be time-consuming and labor-intensive.

In recent years, machine learning techniques have emerged as powerful tools for analyzing symptoms associated with complex conditions such as heart disease, diabetes, and cancer. These methods are now increasingly being applied to ASD detection, with researchers [4], [5] developing a range of models to improve the accuracy and efficiency of diagnosis and help mitigate the effects of ASD more effectively.

The prevalence of ASD has been increasing rapidly across all age groups in recent years. Early detection of this neurodevelopmental condition is crucial, as it can significantly improve the individual's mental and physical well-being. With the growing application of machine learning in healthcare, early diagnosis of various neurological and physiological conditions is becoming increasingly feasible. This progress has fueled growing interest in utilizing these technologies to enhance the detection and analysis of complex disorders, thereby enabling more effective treatment strategies. However, diagnosing ASD remains challenging due to symptom overlap with other mental health conditions. These similarities often complicate the diagnostic process, making accurate and timely identification of ASD a difficult task. This underscores the need for advanced computational tools, such as machine learning models, to support clinicians in distinguishing ASD from related disorders [6].

2 RELATED WORK

Recent studies have explored the use of wearable sensor-based devices for the detection of Autism Spectrum Disorder (ASD) [7], [8]. The integration of intelligent systems has introduced more cost-effective and scalable solutions for identifying ASD in children, adolescents and adults [9]. A wide range of methods has been applied in the literature, including structural magnetic resonance imaging (MRI) [10], neural networks, machine learning (ML) techniques, deep learning, transfer learning, and Internet of Things (IoT) – based frameworks [11]. While these approaches have shown promising results in ASD detection with reasonable accuracy, they are often hindered by data acquisition challenges. Many healthcare institutions are reluctant to share patient data due to organizational policies and regional data protection regulations, making data privacy, security, and availability major obstacles in the development of effective intelligent diagnostic systems. Furthermore, even when data access is granted, transmitting large volumes of data over networks introduces additional concerns such as network congestion, latency and potential data breaches.

Wong et al. [12] utilized data mining tools to investigate the impact of various autism treatments on behavioral outcomes. Their approach enabled the prediction and better understanding of autistic children's behavior, providing a framework for differentiating between socially acceptable and unacceptable conduct. Similarly, Kaur et al. [13] conducted a comprehensive review of 45 research studies that employed supervised machine learning and classification algorithms in the context of ASD diagnosis and analysis. Among the most frequently used models were Support Vector Machine (SVM), Neural Networks, Random Forests, Decision Tree, Least Absolute Shrinkage, and Selection Operator (LASSO), various regression methods, Conditional Forests (CF), Naïve Bayes (NB), Elastic Net regression (Enet), Random Tree, and Flex Tree classifiers. Furthermore Koumpouros et al. [14] carried out a systematic review of 83 studies published after the year 2000, focusing on interventions for ASD that leveraged wearable technologies and computation methods to support treatment and behavioral monitoring.

3 DATA

The following section describes the dataset preprocessing, model selection, hyperparameter tuning, and performance evaluation procedures used to assess the effectiveness of various machine learning models for predicting ASD.

Three datasets are used for the purpose of this paper, one for children, one for adolescents, and one for adults. Every dataset consists of 20 features, 10 of which (A1-A10) are behavioral features that have a binary value (value that is 0 or 1). The other 10 features are shown in Table 1 [15]-[17].

Table 1: Dataset features.

Feature	Description
age	Age in years
gender	Male or female
ethnicity	List of common ethnicities in text format
jaundice	Whether the person was born with jaundice
autism	Whether any immediate family member has ASD
country_of_res	List of countries in text format
used_app_before	Whether the user has used a screening app
result	The final score obtained based on the scoring algorithm of the screening method used. This was computed in an automated manner
age_desc	The age span of the patient
relation	Who diagnosed the patient

For this paper, in addition to the analysis done on these datasets, containing the same features, we constructed a dataset that is a combination of all three. The analysis of the combined dataset gives another view of the results.

The target variable, Class/ASD, was categorical, representing the presence or absence of ASD. To enable machine learning algorithms to process this variable, Label Encoding [19] is applied, where the classes were transformed into binary numeric values: 0 for negative and 1 for positive cases.

4 METHODS

For this study, six machine learning models were selected for comparison:

- Logistic Regression: A linear classifier suitable for binary classification tasks [22];
- Support Vector Machine (SVM): A non-linear classifier that maximizes the margin between classes using kernels [23];
- Decision Tree: A recursive partitioning method that constructs decision boundaries based on features. [24];
- Random Forests: An ensemble model that aggregates the predictions of multiple Decision Trees [20];
- XGBoost: A gradient boosting method known for its robustness and performance [25];
- k-Nearest Neighbors (kNN): A non-parametric method that assigns labels based on the majority vote of neighboring points [26].

5 EXPERIMENTAL SETUP

Initially, a traditional train-validation-test split was implemented to evaluate model performance [18]. However, this method resulted in inconsistent and unreliable evaluation metrics, likely due to the limited size and potential variability within the dataset. To address these limitations, the study adopted a 10-fold cross-validation strategy, which better maintains class proportions across folds and provides more stable and generalizable evaluation results [32].

In 10-fold Stratified Cross-Validation, the dataset was divided into ten equal-sized folds, ensuring that each fold preserved the same class distribution as the overall dataset. The model was trained on nine folds and tested on the remaining fold, and this process was repeated 10 times. The final reported metrics were the average values across all folds.

5.1 Feature Selection

Feature selection is performed using a Random Forest Classifier, to identify the most important predictors of ASD. Random Forest, an ensemble method, computes the importance of each feature by measuring how much they contribute to the reduction of impurity in the Decision Trees [20]. The topmost important feature was identified and subsequently dropped to assess the effect of excluding this feature on model performance. This step was essential for ensuring that the model was not overly reliant on a single feature, which could lead to overfitting.

5.2 Hyperparameter Tuning

To optimize the performance of the models, hyperparameter tuning was performed using GridSearchCV [21]. This method exhaustively searches through a specified parameter grid to identify the best combination of hyperparameters for each model. The hyperparameters tuned for each model included regularization strength (c) for Logistic Regression and SVM, maximum tree depth and minimum samples for Decision Trees and Random Forests, number of neighbors for kNN and learning rate, tree depth, and number of estimators for XGBoost. The hyperparameters were selected based on accuracy as the scoring metric.

5.3 Evaluation Metrics

The metrics that were computed to assess the performance of each model are:

- Accuracy – Measures the proportion of correctly classified instances among all instances [28];
- Precision – Measures the proportion of correctly predicted positive instances among all predicted positives [29];
- Recall – Measures the proportion of correctly predicted positive instances among all actual positives [29];
- F1 Score – Represents the harmonic mean of precision and recall, balancing the two [30];
- Area Under the ROC Curve (AUC) – Evaluates model's ability to distinguish between classes across all threshold settings [31].

These metrics were selected to provide a comprehensive evaluation of predictive ability, especially considering the potential imbalance in class distributions [27].

6 RESULTS

This section presents the results of the descriptive analysis and model evaluation. It explores the distribution of demographic and target features across children, adolescent and adult datasets, followed by performance of six classification algorithms. The analysis is then replicated on a merged dataset to assess model behavior across a combined population.

6.1 Exploratory Data Analysis

To understand the class balance of the dataset across different age groups, the distribution of the target variable (Class/ASD) was visualized separately for children, adolescents and adults.

The class distribution varies across datasets. The children dataset is relatively balanced, with nearly equal numbers of ASD-positive and negative cases, which minimizes bias during model training. In contrast, the adolescent dataset shows a mild skew toward ASD-positive cases, which may influence sensitivity and false positive rates. The adult dataset is strongly imbalanced, with a much higher proportion on ASD-negative cases. This imbalance can hinder the detection of positive cases and may require techniques such as stratified cross-validation or class weighting.

The approximate values of the target variable distribution are illustrated in Table 2 below.

Table 2: Target variable distribution.

Dataset	NO	YES
Children	49%	51%
Adolescents	38%	62%
Adults	72%	28%

To better understand the demographics of each dataset and assess potential biases, the distribution of age was visualized for the children, adolescent, and adult datasets (Figure 1).

The age distribution varies notably across the three datasets. In the children group (ages 4-11), the highest concentration of participants is at age 4 (n≈78), after which the numbers decline steadily with age. This pattern reflects the priority given to early ASD screening, often beginning in preschool years [33].

Among adolescents (ages 12-16), the distribution is relatively even, with each year represented (n≈14-29), and a slight peak at age 16. This indicates that diagnoses continue into adolescence, often due to increased social and academic pressure [34].

In adults (ages 18-80), the distribution peaks in early adulthood (ages 18-25, n≈90) before gradually tapering off with age. This suggests that while most adult diagnoses occur in early adulthood there is still a presence of individuals diagnosed later in life, possibly due to retrospective recognition of lifelong traits or increasing public and clinical awareness of ASD [35].

Analysis of ethnicity across age groups revealed distinct demographic patterns. In the children dataset, White-European participants make up nearly half the sample, followed by Asian and Middle Eastern groups, with minority representation remaining limited underscoring persistent disparities in early ASD diagnosis across ethic lines [36].

Among adolescents, White-European representation decreases slightly, while "Others," Black, and Hispanic groups increase, suggesting broader diagnostic access and improved outreach [37].

The adult dataset shows the most diversity, with White-Europeans below 40% and strong representation from Asian, Middle Eastern, South Asian, Black, and Latino groups, reflecting greater awareness and inclusivity in adult diagnoses.

The gender distribution across the three age groups – children, adolescents and adults – was evaluated to understand the demographic composition of the dataset (Table 3). The gender distribution for children, exhibits a noticeable imbalance, with the number of males being significantly higher than females. This disproportionate representation aligns with the existing research which indicates a higher prevalence of ASD diagnoses among male children compared to female [38].

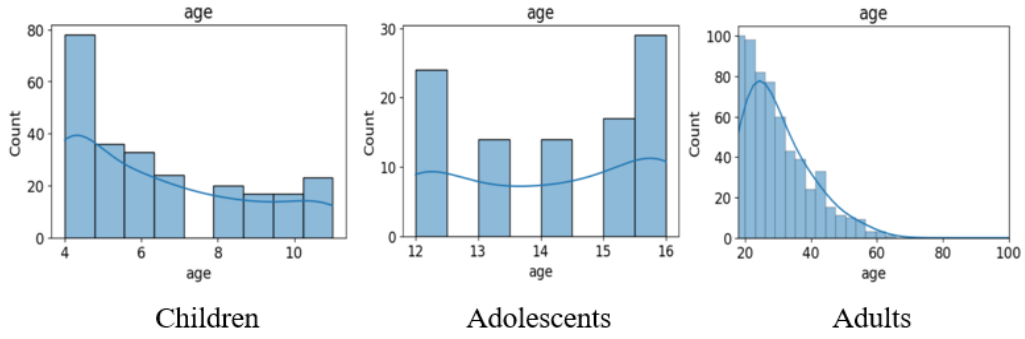


Figure 1: Age distribution across age groups.

In the adolescent group, the gender distribution achieves near parity, with 50 males, and 50 females represented. This balanced composition ensures that the models trained on this dataset are less likely to exhibit gender-related biases, enabling a fair evaluation of ASD detection across both genders in this age group.

The adult dataset demonstrates a relatively balanced gender distribution, albeit with a slight skew. While not perfectly balanced, this distribution provides sufficient representation of both genders to minimize bias in the analysis of ASD detection among adults.

Table 3: Gender distribution across age groups.

Dataset	Male	Female
Children	70%	30%
Adolescents	50%	50%
Adults	53.3%	46.7%

Jaundice, particularly neonatal, has been studied for its potential association with neurodevelopmental disorders, including ASD. Neonatal jaundice results from elevate bilirubin levels, which, if untreated, may lead to kernicterus – a condition that can cause brain damage [39]. In the dataset, most children do not have a history of jaundice. For adolescents, jaundice is even rarer, while in adults, the majority also report no history (Table 4). Overall jaundice is an uncommon feature across all age groups, however, its presence in early life has been linked to potential neurodevelopmental impacts, which could have implications for ASD detection [40].

Table 4: Jaundice distribution across age groups.

Dataset	YES	NO
Children	22.2%	77.8%
Adolescents	18.4%	81.6%
Adults	8.1%	91.9%

6.2 Model Evaluation by Age Group

In this section, the evaluation results of the machine learning models used to predict ASD, across different age groups are presented. The performance of each model is assessed using several key metrics, including accuracy, precision, recall, F1 Score and AUC. These metrics provide a comprehensive understanding of how well each model performs in terms of classification accuracy, the ability to detect true ASD cases and the balance between false positives and false negatives.

Table 5: Model comparison for the children database.

Model	Accuracy (%)	Precision (%)	Recall (%)	F1 Score (%)	AUC (%)
Log Reg	95.58	95.64	96.09	95.77	95.54
SVM	95.2	94.3	96.86	95.43	95.16
kNN	84.35	79.05	96.79	86.59	84.23
Decision Tree	87.52	85.07	92.05	88.24	87.53
Random Forests	94.77	94.89	95.38	94.95	94.84
XGBoost	95.57	95.49	96.09	95.69	95.57

As shown in Table 5, for the children's dataset shows that Logistic Regression and XGBoost perform very similarly across all metrics, making them strong candidates for the children's dataset. SVM has high recall but lower precision, indicating a tendency toward false positives. kNN performs the worst overall, with low accuracy, precision, and F1 score despite high recall. The Decision Tree is balanced but lags behind the top models in precision and F1 score, indicating room for improvement. Random Forest is reliable and comparable to XGBoost but slightly lower in accuracy, precision, and F1.

Table 6: Model comparison for the adolescent dataset.

Model	Accuracy (%)	Precision (%)	Recall (%)	F1 Score (%)	AUC (%)
Log Reg	90	92.74	91.9	91.99	89.29
SVM	89.89	88.87	96.67	92.25	87.5
kNN	73.56	71.4	98.57	82.68	63.87
Decision Tree	74.78	80.77	80.95	79.6	72.14
Random Forests	88.78	87.78	96.67	91.69	85.42
XGBoost	86.78	88.12	91.9	89.62	84.29

According to the evaluation results shown in Table 6, Logistic Regression is the top-performing model for the adolescent dataset, with high precision (92.74%) and recall (91.9%), making it a balanced and reliable choice. SVM has strong recall but lower precision, leading to more false positives. kNN has high recall (98.57%) but low precision and F1, reducing overall effectiveness. Decision Tree is balanced but suboptimal, while Random Forest and XGBoost perform well but slightly behind Logistic Regression in precision and F1.

Table 7: Model comparison for the adult dataset.

Model	Accuracy (%)	Precision (%)	Recall (%)	F1 Score (%)	AUC (%)
Log Reg	97.53	96.59	95	95.75	96.8
SVM	96.22	94.42	92.78	93.5	95.22
kNN	84.35	84.03	86.11	84.94	89.56
Decision Tree	88.99	82.44	80.56	81.09	86.54
Random Forests	96.06	95.58	90.56	92.83	94.46
XGBoost	97.53	96.66	95	95.76	96.8

Table 7, shows that Logistic Regression and XGBoost are the top models for the adult dataset, with the highest accuracy (~97.53%) and excellent precision, recall, F1, and AUC, indicating strong and consistent classification of ASD cases. SVM performs well but slightly below the top models. Random Forest is solid but less consistent, kNN shows moderate performance with lower precision and F1, and Decision Tree performs the weakest overall.

6.3 Analysis on the Combined Dataset

The models were also evaluated on a combined dataset that merges data from children, adolescents, and adults to assess overall performance across age groups. As with age-specific analyses, 10-fold stratified cross-validation was used, and performance was measured using accuracy, precision, recall, F1 score, and AUC. The evaluation results are shown in Table 8.

Table 8: Model comparison for the combined dataset.

Model	Accuracy (%)	Precision (%)	Recall (%)	F1 Score (%)	AUC (%)
Log Reg	97.38	97.02	96.19	96.58	97.16
SVM	96.12	94.64	95.38	94.99	95.98
kNN	82.2	74.17	83.13	78.28	82.37
Decision Tree	87.85	83.28	85.87	84.46	87.48
Random Forests	95.19	95.05	93.4	93.64	94.67
XGBoost	98.22	97.85	97.54	97.68	98.09

The findings from the combined dataset underscore key factors in developing a unified model effective across all age groups. XGBoost proved to be the most effective, achieving high sensitivity and specificity, which is crucial in clinical screening where minimizing both false positives and false negatives is essential. Its strong performance across varied age-related features demonstrates robustness and adaptability, Likewise, Logistic Regression showed consistent results, confirming its reliability for classification tasks involving structured clinical data.

7 DISCUSSION

The comparative analysis of the six machine learning models revealed distinct performance patters across age groups, prompting further interpretation of their mechanisms and suitability for ASD detection.

The superior performance of Logistic Regression and XGBoost can be attributed to their model design advantages. Logistic Regression performs well because the dataset's features show strong, mostly linear relationship with ASD diagnosis, allowing for a simple and generalizable decision boundary.

In contrast XGBoost, effectively captured complex, non-linear feature interaction through its ensemble of decision trees, providing strong adaptability and robustness.

The comparatively weaker and less stable performance of kNN and Decision Tree aligns with expectations. Decision Tree models are prone to overfitting, while kNN's distance-based approach struggles with high-dimensional data, leading to inconsistent performance.

Error analysis showed that the models struggled with individuals whose features were borderline for ASD or who showed mild symptoms, leading to more false negatives, especially among adults, where learned social behaviors can mask ASD traits. Future work should include more detailed feature analysis to improve accuracy in these borderline cases.

8 CONCLUSIONS

This study evaluated six machine learning models for detecting ASD across children, adolescents, and adults, using Accuracy, Precision, Recall, F1 Score, and AUC as performance metrics.

The study concludes that machine learning models, specifically Logistic Regression and XGBoost, provide a robust and generalizable

foundation for early non-invasive ASD screening across all age groups. However, the limitations of this work must be acknowledged. Firstly, the models are trained solely on structured clinical questionnaire data, and do not incorporate time-series behavioral, genetic, or brain-imaging data. Secondly, the model performance, particularly on the adult dataset strongly influenced by the demographic and cultural background of the data, so clinical validation on diverse populations is essential before wider use.

In practice clinicians could input patient assessment data into the model, which would provide a risk estimate to support further evaluation or referral, supporting informed clinical decisions without replacing professional judgment.

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AI-Driven Medical Education for Personalized Health

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Abstract: The present study explores the integration of AI-driven solutions in the education of medical professionals and their role in achieving high-quality healthcare and personalized strategies. A range of AI tools is examined to evaluate how they shape training environments, support medical students during their studies, and influence their later professional practice. The primary objective is to analyze how AI contributes to the advancement of medical education and the transfer of acquired knowledge into daily clinical routines. While AI enables rapid access to information and decision support, medical professionals must also maintain the ability to make accurate judgments under pressure. This raises concerns about whether reliance on AI during training may reduce students' capacity for independent and rapid clinical reasoning. The study further investigates the extent to which AI-based simulations can provide realistic and comprehensive training experiences. Beyond replicating surgical procedures, it is critical to assess whether such systems can recreate the psychological, emotional, and tactile aspects of practice—such as stress management, operating under pressure, and the physical sensations of interacting with human tissue. Special emphasis is placed on identifying the benefits for patients, particularly whether AI-enhanced education ultimately contributes to more effective, personalized healthcare outcomes.

1 INTRODUCTION

Digital technologies, especially AI, have become a huge part of our daily lives. They're involved in so many areas like education, healthcare, retail, and even navigation on ships. What's even more interesting is how these technologies are linking these areas together in ways we didn't expect before. This is making it even more important for us to use them well, and also to be able to adapt ourselves and adjust these tools to fit our personal needs.

One example of this is how animal testing is being replaced with simulations [1], [2]. More and more, computer-based models are being used to train medical students, simulating things like blood tests, patient behavior, different reactions, or even emergencies. This shift is not only more ethical but also opens up the possibility for better and more efficient learning.

The main goal of all of this is to improve healthcare, to make sure medical professionals are well-prepared, and to reduce preventable mistakes. In the research, we will look into how AI is already being used in medical education, how it affects the learning of students, and how this knowledge is applied when they become practicing doctors. We'll also explore the consequences and impacts of bringing AI into medical training. The core argument of this study is that AI does not contribute to the development of empathy toward patients.

2 METHODS

2.1 Literature Review

This study includes a narrative review of the current literature on AI technologies in medical education and personalized healthcare. Sources were identified through keyword searches in databases such as Scopus, Spinger Natura, ResearchGate and PubMed using terms like "artificial intelligence", "medical education", "personalized medicine", and "adaptive learning". The review focused on papers published between 2004 and 2025. Only peer-reviewed articles and reputable conference papers in English were included. The aim was to summarize key trends, challenges, and research gaps relevant to the study topic.

2.2 An Online Survey

An online survey was conducted using Google Forms between April and May 2025. The participants included medical students and faculty members from various institutions in Bulgaria. A total of 68 responses were collected. Although the sample size is relatively limited, this reflects the current early stage of integration of AI-based training tools and simulations in Bulgarian medical education. As such technologies are not yet widely implemented, the study serves as an initial exploration of awareness and attitudes. The survey consisted of fully anonymous questions focused on perceptions, interest, and expectations related to AI in medical learning contexts. No demographic data were collected, as the study aimed to capture general attitudes and experiences, rather than conduct subgroup analysis. Moreover, the anonymous nature of the questionnaire was intended to encourage candid responses.

3 AI TOOLS IN MEDICAL EDUCATION – TYPES AND MODELS

AI in the fields of medical education can influence the student learning process in different ways [3]. There are different types of AI tools, and they serve different purposes. Practice indicates that the use of AI in medical education fosters critical thinking and the ability to make rapid decisions [4]. However, not all studies support this view, some suggest the opposite [5].

3.1 Virtual Patients - Simulation of Real Patient Cases

Virtual patient is a computer simulation of a real patient which is used in education for students or medical specialists. The virtual patient has symptoms, test results, and even AI tools that provide patient responses based on the user's choices. This happens without any risk, unlike with real patients [3]. Machine learning is incorporated to interpret laboratory data accurately and defect abnormal values [3], [6].

3.2 AI Robots in Surgery and Surgery Simulation

These Procedural skills can be assessed with Virtual Reality, where a simulated patient will be presented in a virtual environment, and the learner is asked to do a procedure [3]. Simulation training is one method of developing proficiency in a safe and risk-free environment and is used in formal surgical training [7]-[10]. One of the examples in this category is Touch surgery software - an effective instrument for medical student education that aims to teach surgical decision making to trainees without risk to patients [7]. Trainees can continue their learning during actual procedures using AI driven robotic systems [11].

The research shows that while AI is improving procedural safety, they also led to unintended negative effects on certain technical skills (like hands movement during surgery) [12].

3.3 AI Patient Diagnosis and Prescription - Chatbots

AI is integrated into medical education through the use of virtual patient simulations and surgical simulations, enabling students to develop skills in diagnosis and treatment planning. Furthermore, AI tools continue to support physicians after graduation by assisting them in real clinical environments. One of the most used AI tools is ChatGPT, with 66.7% of the 207 surveyed students reporting familiarity with it [13].

After graduation, specialists continue to use AI in their practice for patient diagnosis. DXplain is a big example; it is a clinical decision support system. The system assists healthcare professionals by providing a list of potential diagnoses based on the input of clinical findings, including symptoms, signs, and lab results [14].

Similar AI tools are AMIE (a Large Language Model - based AI) [15], [16] and FAMULUS (a Natural Language Processing model) [17]. Stanford Graduate School of Education is using web-based platforms to help medical students improve their ability to determinate a patient's initial diagnosis and treatment. It is called Clinical Mind AI [18]. The last one is documented in Standford Graduate School of Education paper. These tools provide high-quality consultations tailored to the personalized needs of patients [16].

3.4 AI Knowledge in Practice

Artificial intelligence is still not widely integrated into medical education. Studies show that approximately 75% of students in medicine, veterinary medicine, and dentistry have not received training involving AI [19]. At the same time, research indicates that students who have used AI during their education often continue or intend to use it in their

future professional practice, with most of them expressing a positive attitude towards AI [20]-[22].

3.5 AI-Enhanced Empathy Toward Patients

Simulation based education, especially in the medical field, significantly improves not only technical skills but also non-technical skills like teamwork and communication [23]-[26]. The focus is also on improving patient relationships by fostering empathy in students during their training phase. Dialogflow is representative of these types of AI systems. There are chatbots specifically designed to enhance communication skills through simulated patient interactions. These systems use an AI interface combined with Natural Language Processing (NLP) to understand and process human -language, enabling students to practice their empathy and communication skills in a realistic, controlled environment [27].

Despite all the benefits, concerns remain in the scientific community that the use of AI may compromise the quality of patient care, undermine the trust between physician and patient, reduce empathy, or diminish the humanistic aspect of medicine [22], [28], [29]. These concerns are not only reflected in research but are also shared by medical students themselves [30]. As previously mentioned, there are also conflicting views regarding the impact of AI on the development of critical thinking skills [5].

However, although these benefits are well recognized, the existing evidence does not clearly demonstrate that such improvements translate into greater empathy or more effective communication with patients. Rather, the gains in non-technical skills may primarily pertain to interactions within clinical teams rather than patient-centered communication [31]-[33].

4 USER SURVEY VIA GOOGLE FORMS

A survey was conducted among medical students and faculty members with the aim of exploring their attitudes toward the development of emotional connection and empathy in the patient-caregiver relationship. The objective was to investigate perceptions regarding the role of emotional competence in clinical practice, particularly in the context of medical training and education.

A total of 68 participants took part in the survey during the period April–May 2025. Although the sample size is relatively small, this can be attributed to the still limited integration of artificial intelligence technologies in medical education in Bulgaria, which may have influenced both awareness and interest in the topic. In addition, demographic data were not collected, as the primary aim of the study was to explore general attitudes and perceptions, rather than perform subgroup analysis. The survey was distributed via student groups on social media and among students and faculty from a university offering programs in human medicine, veterinary medicine, and related health sciences.

4.1 Participants

A total of 68 participants took part in the survey. Of these, 50% (n = 34) were medical students, 5.9% (n = 4) were medical educators, 11.8% (n = 8) were healthcare professionals who are not students or educators in medical schools but work within the healthcare sector, 27.9% (n = 19) were other medical professionals, such as doctors and nurses, and 4.5% (n = 3) were individuals not related to the medical field. The detailed distribution is present in Table 1.

The study divided participants into two groups based on whether they answered AI helped them better understand patients' needs. Given the aim of the study - to evaluate the impact of artificial intelligence on understanding patients in a medical context - only participants with a relevant academic or professional background in medicine were included in the analysis (only medical students and educators). These were medical students and educators, as their perspectives are directly related to clinical practice and medical education. Including other participants would have diluted the results and shifted the focus away from the specific medical context.

For the purposes of the quantitative analysis, only respondents who provided a clear and definitive answer ('Yes' or 'No') to the question of whether AI helped them better understand patients were included. Responses such as 'Not sure' or 'Other' were excluded, as they do not allow for clear interpretation or direct comparison in the context of binary analysis. This approach ensures greater clarity and statistical validity of the results.

4.2 Analysis

The paper Group YES included 16 participants who answered "Yes," and Group NO included 11 participants who answered "No." The groups were

compared across several questions to examine the role of AI in emotional connection, emotional preparation, and empathy development. The comparative results are summarized in Figure 1.

Table 1. Overall survey results.

Questions				
Do you think using artificial intelligence (AI) in your education has improved your ability to understand patients' needs?	Yes 44.1% (30)	No 23.5% (16)	Not sure 29.4% (20)	Other 3% (2)
How often do you interact with real patients compared to digital simulations during your training?	More than 80% of the time 36.8% (25)	21–40% of the time 27.9% (19)	Less than 20% of the time 29.4% (20)	Other 4.5% (3)
Do you feel that AI tools in your education help you prepare for an emotional response to patients?	Yes 19.1% (13)	No 45.6% (31)	Not sure 32.4% (22)	Other 3% (2)
Have you ever felt overly dependent on AI in your education or work?	Yes 19.1% (13)	No 79.4% (54)	Sometimes 1.5% (1)	- - -
How would you rate your ability to emotionally connect with patients before and after the introduction of AI in your training?	AI did not help me better understand the emotional state of patients 58.8% (40)	AI helped me better understand the emotional state of patients 13.2% (9)	Not sure 23.5% (16)	Other 4.5% (3)
Do you believe that remote learning in medical education is as effective as traditional face-to-face methods?	Yes 17.6% (12)	No 69.1% (47)	Not sure 11.8% (8)	Heavily dependent on goals of education/ student learning 1.5% (1)
Have you experienced a lack of motivation or connection to the learning process during digital training?	Yes 60.3% (41)	No 22.1% (15)	Not sure 16.2% (11)	NA 1.5% (1)
In your opinion, can fully digitalized education effectively prepare future doctors?	Yes 10.3% (7)	No 77.9% (53)	Not sure 11.8% (8)	- - -
Do you believe that technology in medical education should always be balanced with real human interaction?	Yes 91.2% (62)	No 7.4% (5)	Heavily dependent on goals of education/student learning 11.5% (1)	- - -

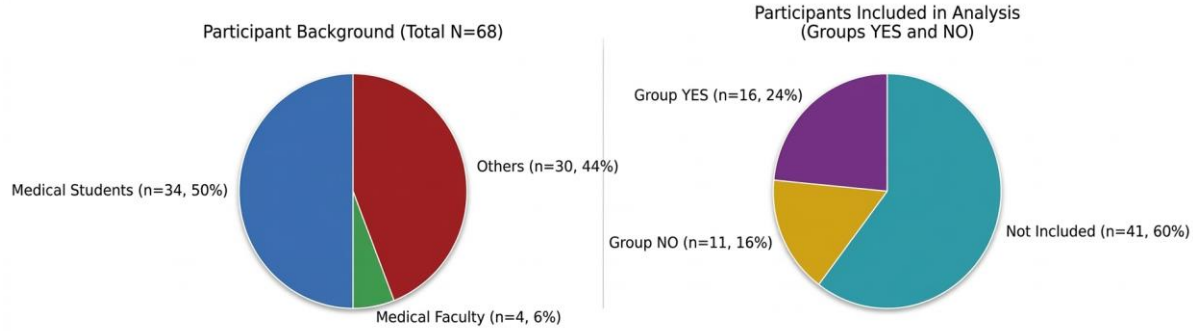


Figure 1: Analyzed groups.

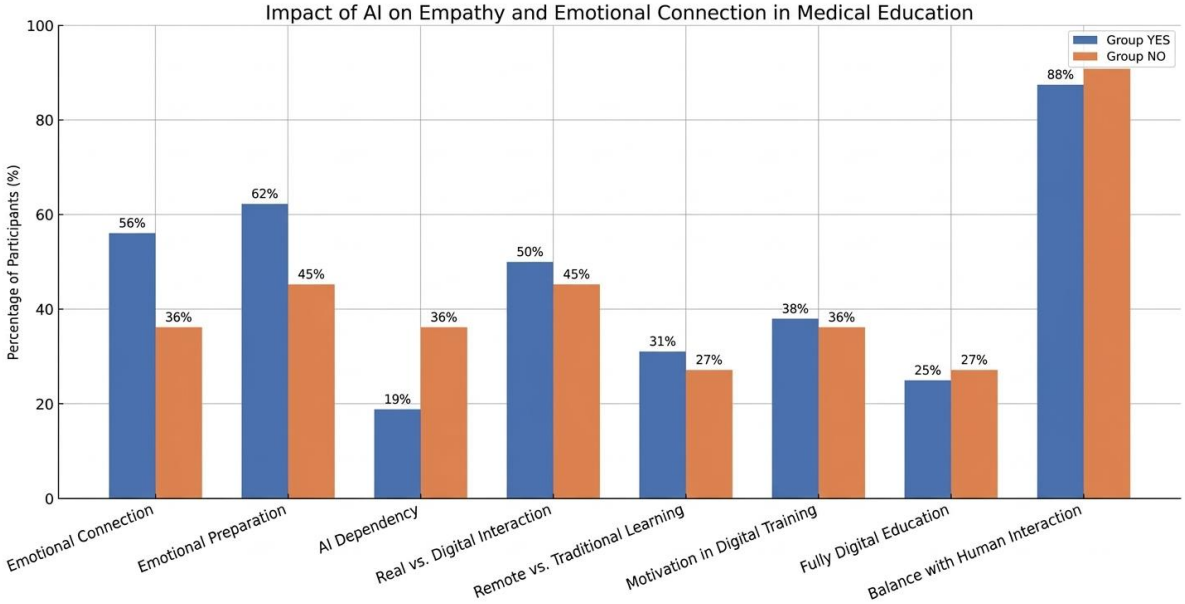


Figure 2: Perceived impact of AI on empathy development in medical education.

Regarding the question of whether AI helps emotionally connect with patients, the Chi-square statistic was 3.365 with a p-value of 0.131, indicating no significant difference between the groups. This suggests that AI did not significantly enhance emotional connection with patients, supporting the thesis that AI does not contribute to empathy development.

On whether AI tools help prepare for emotional responses to patients, the Chi-square statistic was 5.23 with a p-value of 0.157, again showing no significant difference. This indicates that AI does not play a major role in emotional preparation, further suggesting its limited impact on empathy. When asked about dependency on AI, Group YES had 3 participants reporting dependence, while Group NO had 4. The Chi-square statistic was 1.70 with a p-value of 0.192, meaning there was no significant difference between the groups, indicating that AI does not foster reliance that could replace emotional intelligence.

In terms of real patient interaction versus digital simulations, the Chi-square statistic was 4.22 with a p-value of 0.241, showing no significant difference. This suggests that AI does not influence the frequency of real patient interaction, meaning it does not enhance empathetic connections.

Regarding the effectiveness of remote learning compared to traditional face-to-face methods, the Chi-square statistic was 4.52 with a p-value of 0.212. Both groups preferred traditional methods, and the lack of impact on empathy suggests that AI-driven remote learning does not enhance emotional connection with patients.

On motivation during digital training, the Chi-square statistic was 1.89 with a p-value of 0.389,

showing no significant difference between the groups. This implies that AI did not improve motivation or engagement, further supporting the idea that AI lacks an emotional connection-building role.

When asked if fully digital education could prepare future doctors, the Chi-square statistic was 0.85 with a p-value of 0.356, indicating no significant difference. Both groups believed fully digital education was insufficient, suggesting that AI cannot replace the human interaction necessary for empathy development.

Finally, on whether technology should always be balanced with human interaction, the Chi-square statistic was 1.83 with a p-value of 0.400. Both groups overwhelmingly agreed that human interaction is essential, reinforcing the idea that AI does not replace the need for human empathy in medical training. These findings are presented in Figure 2.

5 CONCLUSIONS

In conclusion, The Chi-square tests for all questions showed no statistically significant differences between the two groups (p-values greater than 0.05 in all cases). While these results align with the hypothesis that AI may not have a significant impact on improving empathy or emotional connection with patients, it is important to note that the sample size was relatively small. Therefore, there is insufficient evidence to definitively support this thesis. Further research and larger studies are needed, as existing studies on AI's effect on empathy towards patients are limited or lacking.

Moreover, the findings suggest that while AI-driven tools can enhance technical knowledge and procedural skills, they may not adequately address the humanistic aspects of medical training. The ability to understand patients' emotions, communicate effectively, and build trust remains largely dependent on real-world interactions and mentorship from experienced practitioners. This highlights the need for medical curricula to balance technological innovation with opportunities for direct patient engagement and reflective practice.

Additionally, the study underscores the importance of evaluating the long-term implications of AI integration in medical education. While students may demonstrate improved efficiency in diagnosis or procedural simulations, it is still unclear how these skills translate to bedside competence, particularly in emotionally challenging scenarios. AI should therefore be viewed as a complementary tool rather than a replacement for traditional educational methods that foster empathy and ethical decision-making.

Furthermore, the survey responses indicate a general consensus among participants that human interaction cannot be fully substituted by digital simulations or AI-based training. This reinforces the necessity for hybrid educational models where AI technologies are integrated alongside patient-centered teaching methods. Such approaches could ensure that future healthcare professionals are not only technically proficient but also capable of providing compassionate and personalized care.

Finally, these results highlight critical areas for future research, including the development of AI applications that better simulate emotional and interpersonal dimensions of medical practice, as well as longitudinal studies to track the impact of AI exposure on professional behavior and patient outcomes. By addressing these gaps, educators and researchers can better harness the potential of AI while preserving the essential human qualities that define effective healthcare provision.

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Brain Tumor Classifications Using MRI Scans with Deep Learning

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Keywords: Brain Tumor, Magnetic Resonance Imaging, Deep Learning, Convolutional Neural Networks, Medical Image Analysis.

Abstract: This paper focuses on the detection and classification of brain tumors using MRI images and Deep Learning methods. The dataset consists of 7,023 MRI scans representing healthy brains and brains with glioma, meningioma, or pituitary tumors. We developed and evaluated Convolutional Neural Network (CNN) models of varying depth, combined with preprocessing techniques such as image resizing, limited augmentation, and validation set allocation to prevent overfitting. The study demonstrates that CNN-based approaches can achieve high accuracy in tumor classification, with the best model reaching an overall accuracy of 98.5%. Results show that the greatest misclassification occurred between glioma and meningioma, reflecting their similar MRI appearance. Further analysis confirms that these tumor types share overlapping visual characteristics, making them more challenging to separate. Overall, the findings highlight that well-designed architectures and carefully controlled preprocessing can significantly enhance automated brain tumor detection, offering valuable support for radiologists and contributing to more efficient, consistent, and reliable diagnostic workflows.

1 INTRODUCTION

Brain tumors are pathological cell growths within or around brain tissue, which can be benign (non-cancerous) or malignant (cancerous). Although benign tumors typically grow more slowly and rarely metastasize, their location can still cause severe neurological impairments due to pressure on brain structures. Brain cancer ranks among the top ten leading causes of mortality worldwide, with specific risk factors including age, radiation exposure, and ethnic or racial background [1]. The World Health Organization (WHO) classifies brain tumors into four grades, based on histological characteristics and their potential to infiltrate surrounding tissue [2]. The most common tumor types in adults are gliomas, meningiomas, and pituitary tumors, while in children, medulloblastomas and other embryonal tumors predominate [3]. The symptoms of brain tumors vary depending on their size and location and may include headaches, seizures, visual and
speech disturbances, paralysis, and hormonal imbalance. Diagnosis typically involves a neurological examination, MRI imaging, and biopsy, with liquid biopsies increasingly being applied to detect tumor markers in recent years [4]. In recent years, machine learning has emerged as an effective approach for tumor detection, enabling the development of models capable not only of identifying tumors but also of classifying them by type. This research focuses on developing a CNN-based model designed for accurate detection and classification of brain tumors.

2 RELATED WORK

In recent years, deep learning (DL) has become a dominant approach for brain tumor classification using MRI images, complementing and often surpassing traditional machine learning (ML) methods. Early ML-based strategies relied on handcrafted features such as intensity, texture, and shape, combined with classifiers like support vector machines (SVM), k-nearest neighbors, or random forests [5]. While these approaches achieved reasonable accuracy, their dependence on manually designed features limited scalability and

generalization. To overcome these limitations, hybrid strategies emerged, where features extracted by convolutional neural networks (CNNs) were fed into ML classifiers, achieving classification accuracies exceeding 90% [6].

Fully CNN-based architectures were also developed for classification and segmentation tasks, reporting accuracies between 90% and 97% under controlled training conditions [7]. Recent work has shifted toward more sophisticated DL frameworks for both classification and segmentation. Multi-scale 3D CNN models, such as DeepMedic, incorporate local and contextual information from MRI volumes, improving segmentation performance [8]. Similarly, multimodal approaches that integrate T1, T2, and FLAIR sequences have enhanced the detection and classification of tumor subregions [9]. Transfer learning using pre-trained networks such as VGG, ResNet, and GoogleNet has proven especially valuable for smaller datasets, enabling robust feature extraction without extensive training [10].

More recently, advanced architectures like multimodal 3D DenseNet leverage multi-sequence MRI data to grade gliomas with high precision [11]. Despite these advances, challenges remain, including the limited availability of annotated datasets, difficulty handling rare tumor types, and generalization across different imaging protocols. These issues underline the ongoing need for hybrid or novel DL architectures that can fully exploit multimodal MRI data while improving classification accuracy and robustness in clinical practice.

3 MACHINE LEARNING FOR BRAIN TUMOR DETECTION

Machine learning, and particularly deep learning, can be applied to the detection and classification of brain tumors [12]. The entire process of developing a model begins with the selection of a dataset that will be used for training. In this study, we employ a dataset consisting of 7,023 MRI images, which include both healthy brains (without tumors) and brains with tumors. The tumors in the dataset belong to three distinct categories. For image analysis, we utilize models based on Convolutional Neural Network (CNN) layers, which are particularly effective for image processing due to their ability to recognize complex spatial patterns and learn hierarchical features. Generally, the process of model development involves several steps: data collection, data preprocessing, model architecture design and training, validation, and testing. In this specific case, the following steps were undertaken:

1) Dataset selection – the aforementioned MRI dataset was selected for model training [13].
2) Data preprocessing – multiple techniques were applied to transform the images into the desired format.
3) Model architecture – three CNN-based models of different depths were constructed for training. The aim was to investigate whether deeper architectures yield improved performance without causing overfitting.
4) Model training – key hyperparameters were adjusted, and the training phase was performed, during which the model was provided with labeled data to learn correct classification.
5) Validation and testing – validation was used to monitor how the model performs on previously unseen data, while testing represented the final phase, providing accuracy results on a separate set of entirely new data (unseen by the model during training).

4 DATASET AND PREPROCESSING

4.1 Dataset

The dataset consists of 7,023 MRI images divided into four categories:

1) No tumor: 2,000 healthy brain images.
2) Glioma: 1,621 images of malignant tumors originating from glial cells.
3) Meningioma: 1,645 images of tumors arising in the meninges.
4) Pituitary tumor: 1,757 images of tumors located in the pituitary gland.

Figure 1 presents representative examples of MRI scans from each class, while Figure 2 illustrates the distribution of images across the four categories.

4.2 Data Preprocessing

Preprocessing is a crucial step in medical image analysis, as it ensures that the input data is standardized and suitable for effective model training. In this study, two preprocessing techniques were applied during data loading: resizing and augmentation. Resizing was performed to standardize all images to the same dimensions, allowing consistent transformation and use in both training and testing.

Augmentation involved applying slight transformations and rotations to the training images. Specifically, the augmentation process included random rotations up to 10°, affine translations of up to 5% along both axes, and slight brightness and contrast adjustments of ±0.05, followed by normalization to a mean of 0.5 and a standard deviation of 0.5. Because the dataset consists of medical scans, the augmentation was intentionally kept minimal to preserve anatomical accuracy. Furthermore, 20% of the training set was allocated for validation, enabling evaluation of the model's performance on unseen data and helping to prevent overfitting.

5 MODEL ARCHITECTURE

In this study, three Convolutional Neural Network (CNN) models were developed, all sharing the same core architecture but differing in depth. Each model is composed of the following layers:

- Conv2d – a two-dimensional convolutional layer commonly used for image processing. By passing the input image through convolutional filters, the layer extracts key spatial patterns that are critical for classification. Deeper networks with multiple convolutional layers can capture increasingly complex features.
- BatchNorm2d – a normalization layer applied to stabilize and accelerate the training process.
- ReLU – a nonlinear activation function that introduces nonlinearity and enhances the representational capacity of CNNs.
- MaxPool2d – a pooling layer that performs downsampling by reducing the spatial dimensions of the feature maps. This decreases the number of parameters and computations, leading to faster training while preserving essential features.
- Dropout – a regularization technique that randomly deactivates a fraction of neurons during training to reduce overfitting.

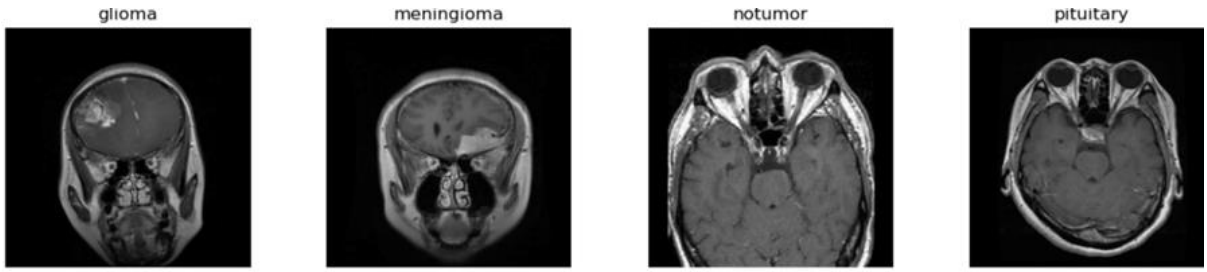


Figure 1: Example images from each class.

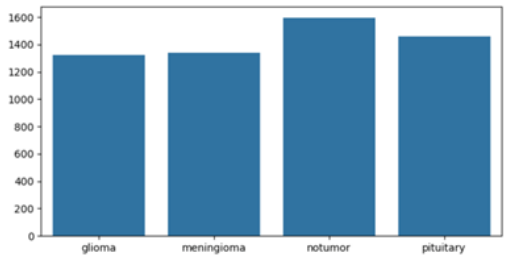


Figure 2: Class distribution.

Table 1: Comparison of model architectures and validation performance.

Model	Trainable parameters	Model size (MB)	Best validation accuracy	Best F1	Epoch of best F1
Base	8,483,588	32.36	0.9011	0.8961	26
Deeper	8,780,548	33.50	0.9466	0.9445	23
Light	16,832,388	64.21	0.8345	0.8287	8

The baseline model consists of three such convolutional blocks, the shallow model of two, and the deep model of four. After defining the architectures, the models were trained using a custom function, which takes the model class as an input. Training was performed for 30 epochs with a batch size of 32 using the Adam optimizer with a learning rate of 0.001 and CrossEntropyLoss as the classification objective, as this configuration provided a stable convergence rate and effectively balanced computational efficiency and generalization performance.

At the end of each epoch, the models were evaluated on the validation set to track accuracy and macro F1 score. To prevent overfitting, an Early Stopping mechanism with a patience of 5 epochs was implemented on the validation set.

This mechanism monitors the best macro F1 score and stops training if no improvement is observed over five consecutive iterations, indicating that continued training could lead to overfitting and a decline in validation performance.

With the established training procedure, the three models can be compared in terms of depth, representational capacity, and generalization performance (Table 1).

The Light model, despite having only two convolutional blocks, incorporates a relatively large fully connected layer, resulting in the highest parameter count (16.83M), which increases its representational capacity but also its susceptibility to overfitting. Consequently, while it trains faster, it achieves lower validation performance (best validation accuracy 0.8345, best F1 0.8287) compared to the other models. The Base model provides a balanced trade-off, with moderate depth and 8.48M parameters, capturing richer hierarchical features than Light while maintaining computational efficiency; it achieves a higher best validation accuracy of 0.9011 and F1 of 0.8961.

The Deeper model further increases representational power through an additional convolutional block and a larger dense layer, totaling 8.78M parameters, enabling it to learn more complex spatial patterns. This architecture attains the highest validation performance among the three (best validation accuracy 0.9466, best F1 0.9445), although with increased computational demand. Overall, this comparison demonstrates that optimal performance is influenced not only by network depth but also by the interaction between parameter count, model complexity, and generalization, emphasizing the importance of balancing capacity and overfitting risk.

6 RESULTS

After training, the models were evaluated using a dedicated function, which accepts the trained model as input. For each model, the confusion matrix, classification report, accuracy, and macro F1 score were computed and stored to enable comparison between models. Model comparison was performed based on the F1 score, and the deepest model achieved the best overall performance according to these metrics. The learning curves of training and validation accuracy for the three models are shown in Figure 3.



Figure 3: Training and validation accuracy curves for Light, Base, and Deep models

The performance of the best-performing (deepest) model was further analyzed using a confusion matrix. The confusion matrix, shown in Figure 4, provides a detailed visualization of correct and incorrect class predictions, highlighting specific patterns of misclassification. The largest misclassification occurred between glioma and meningioma, with 43 glioma images predicted as meningioma. Additionally, 23 meningioma images were misclassified as healthy brains (no tumor). Correctly classified sample images for each tumor type are illustrated in Figure 5, highlighting representative predictions of the deepest model.

Finally, the class-wise performance metrics of the deepest model were visualized, and the per-class recall was reported as follows:

- Glioma: 0.817
- Meningioma: 0.856
- No tumor: 0.985
- Pituitary tumor: 0.993

These values are illustrated in Figure 6, providing a graphical representation of the model's per-class recall. Overall, the figure highlights that the model achieved high accuracy in distinguishing between healthy and tumor-bearing brains, with the most challenging distinction occurring between glioma and meningioma.

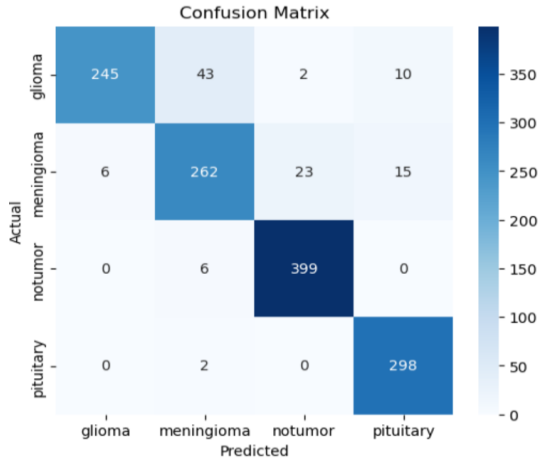


Figure 4: Confusion matrix

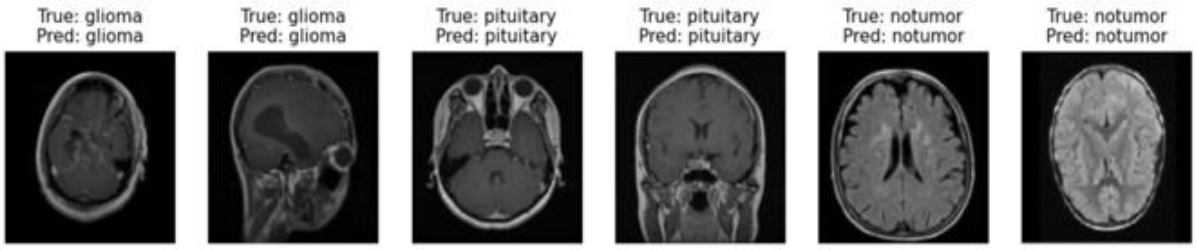


Figure 5: Correctly predicted classes.



Figure 6: Graphical representation of model per-class recall.

7 CONCLUSIONS

The results of this study demonstrate that the developed model for brain tumor detection and classification effectively distinguishes between the different classes. In particular, it achieves high accuracy in determining the presence or absence of a tumor, with an overall accuracy of 98.5%. The greatest misclassification occurred between glioma and meningioma images. This is likely because meningiomas develop exclusively in the meninges, whereas gliomas can arise anywhere in the brain, including regions adjacent to the meninges. In such cases, the model may misclassify the tumor type. Previous studies have confirmed the similarity between these two MRI image types, noting that they can be differentiated based on tumor margins: meningiomas exhibit well-defined boundaries, whereas gliomas often have irregular, blurred edges due to their malignant and infiltrative nature [14]. These findings confirm that Convolutional Neural Networks (CNNs) are a powerful tool for brain tumor classification from MRI scans. With appropriately designed architectures, carefully prepared datasets, and techniques to prevent overfitting, CNN-based models can achieve high accuracy and stability. Although distinguishing certain tumor types remains challenging, integrating additional medical parameters and employing advanced architectures may further enhance the precision of automated diagnostic support systems. For successful translation into clinical practice, the model must be validated on diverse, multi-institutional datasets to ensure robustness across different MRI protocols, scanner types, and patient populations. Integration with existing hospital workflows, including Picture Archiving and Communication Systems (PACS) and electronic health records, is crucial to provide effective decision support for radiologists. Additionally, regulatory approval, compliance with data privacy standards, and ongoing monitoring of model performance are essential to ensure safe and reliable deployment. Addressing these considerations is necessary to translate high experimental accuracy into practical, clinically useful tools, ultimately supporting more accurate, efficient, and informed brain tumor diagnosis and treatment.

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Brain Tumor Mri Segmentation Using A Hybrid Otsu–Fcm Model

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Abstract: The process of segmenting MRI images of brain tumors is one of the essential tasks in image-based medical diagnosis, as it directly contributes to improving the accuracy of determining the tumor's location, shape, and size. However, most segmentation techniques still suffer from poor performance in low-contrast or noisy images due to the overlap of gray levels and the similarity of brain tissues. This study aims to develop an effective hybrid model that combines Otsu's Method and the Fuzzy C-Means (FCM) algorithm, in order to enhance segmentation accuracy and reduce the impact of noise in medical images. The model was implemented using the MATLAB environment and applied to the BraTS 2023 database, which includes MRI images of 1271 patients. The evaluation methodology included the extraction of multiple quantitative indicators such as the Dice coefficient, Mean Squared Error (MSE), Peak Signal-to-Noise Ratio (PSNR), accuracy, recall, and F1 score. The results showed that the hybrid model outperformed the individual methods; the average Dice coefficient was 0.9577, compared to 0.9262 and 0.8955 for the FCM and Otsu methods, respectively. The model also achieved the lowest mean squared error (MSE = 94.58) and the highest PSNR of 29.17 dB, with a classification accuracy of 98%. These results confirm that the proposed model provides an effective balance between computational accuracy and structural flexibility, making it suitable for application in medical decision support systems, especially in analyzing medium or low-quality images without the need for complex deep models.

1 INTRODUCTION

The process of segmenting MRI images of brain tumors is a pivotal task in medical diagnosis, as it significantly contributes to determining the tumor's location, size, and shape, which in turn affects the accuracy of the diagnosis and the surgical or radiotherapy treatment plan. However, the process of automatic segmentation still faces significant technical challenges due to the complex nature of brain tissues, the similarity in density between tissues, the low contrast between the tumor and adjacent areas, as well as the impact of noise and the presence of artifacts in the images. The problem is that most traditional and modern methods suffer from limitations. For example, Otsu's Method shows good accuracy in thresholding, but it is significantly affected by noise and does not perform well in images with a non-homogeneous pixel distribution. In contrast, the Fuzzy C-Means (FCM) clustering algorithm is In this context, a hybrid algorithm was proposed by Cheng et al. (2007) that combines Fuzzy C-Means (FCM) clustering and Otsu's method to improve the accuracy of MRI image segmentation, contributing to noise reduction and enhancing image homogeneity [1]. Min Li et al. developed (2008) an improved model of the Fuzzy C-Means (FCM) algorithm for segmenting MRI brain images by integrating histogram information, which contributed to accelerating the convergence process and reducing the number of iterations, with the ability to automatically determine the optimal number of clusters. The results demonstrated the superiority of this model in terms of accuracy and efficiency compared to traditional FCM and the Fast-FCM algorithm, especially in high-noise data, enhancing its suitability for medical applications with large data volumes [2]. As for (Zhang et al., 2009), they combined Otsu, FCM, and the Roberts algorithm to improve the segmentation of low-contrast images, achieving good results despite not testing the execution speed [3]. And. Karnan and Gopal (2010) presented a hybrid model for segmenting MRI brain

images by integrating the Parallel Ant Colony Optimization algorithm with the Fuzzy C-Means (FCM) algorithm within a Markov Random Field framework, aiming to improve threshold selection and reduce noise impact. The model relied on parallel ant colonies to achieve the lowest possible probabilistic energy before applying FCM, resulting in a significant improvement in the speed and accuracy of segmentation compared to traditional methods [4]. Then, Parveen (2015) & Amritpal Singh combined FCM and SVM after image enhancement and suspicious region identification, resulting in high accuracy, despite challenges in low-contrast images [5]. In contrast, Singh, Das, and Veeramuthu (2017) relied on Spatial Fuzzy C-Means (SFCM) to enhance segmentation accuracy, but the study recommended expanding experiments to confirm effectiveness [6]. In another study by Al-Rawi and Mohammed (2018), a new statistical technique for segmenting multispectral satellite images using Thresholding algorithms was introduced, demonstrating its effectiveness in isolating distinctive environmental areas compared to traditional methods, applied to images of the western region of Iraq [7]. Additionally, Faris et al. (2019) presented a model combining K-means, Watershed, and Otsu to identify tumor regions, achieving good accuracy but with implementation complexity [8]. Then, (Fatemeh Gholami, 2020) developed a model based on FCM supported by swarm intelligence algorithms, achieving high accuracy, but at the cost of computational complexity [9]. In the study by Jaber et al. (2021), a two-phase method for image segmentation was proposed using statistical thresholding techniques [10]. The first stage relied on preprocessing the images through statistical confidence intervals to estimate the unknown observations based on the Acho & Buenestado (2018) model, while the second stage involved applying the Bernsen's Thresholding technique to actually segment the image [18]. The study results showed that combining confidence intervals with the thresholding method improves segmentation accuracy compared to the traditional use of the Bernsen method, whether in the case of original images or in the presence of speckle noise, highlighting the effectiveness of the proposed approach in enhancing image segmentation quality [10]. Othman et al. (2022) also analyzed the performance of FCM and Otsu in evaluating images of osteosarcoma patients, and found that FCM outperformed Otsu in the T1_FSE+GADO sequence, without discussing execution time [11]. Gupta and Jain (2024) demonstrated the effectiveness of Otsu in identifying fusion areas in CT and MRI images, despite not being tested under noisy conditions. [12] Finally, a study by Fajrin and Kim (2024) demonstrated the superiority of U-Net over Otsu and FCM in breast image segmentation, but it highlighted the need for high computational resources without addressing this issue. Based on the above, this research aims to develop a hybrid model that combines the Otsu algorithm and the Fuzzy C-Means algorithm, leveraging the former's accuracy in determining optimal thresholds and the latter's ability to handle structural ambiguity and the non-homogeneous distribution of tissues. This model aims to overcome the limitations [13]. Recent studies have proposed nonlinear algorithms to remove Gaussian noise from space telescope images using advanced filters. Several approaches have been compared in terms of quantitative performance and edge preservation capability. The study recommended adopting unconventional methods to improve image quality in astronomical and space applications [14], as observed in previous studies, by providing a relatively simple framework that is efficient in terms of time and computational accuracy, and suitable for clinical applications. The significance of the research lies in its addressing one of the most prominent issues in medical imaging, which is the accuracy in determining tumor boundaries without the need for high-cost deep models. This model also serves as a step towards simpler and more stable hybrid algorithms, suitable for implementation in medical decision support systems. These studies collectively show that hybrid models, particularly those combining FCM and Otsu's method, are among the most promising techniques in processing magnetic resonance images, as they provide a balance between accuracy and processing efficiency, paving the way for the development of an improved model that overcomes the limitations of previous models.

2 THEORETICAL FRAMEWORK

2.1 Otsu's Method

Otsu's Method is one of the most prominent techniques used in the field of image segmentation, relying on the principle of thresholding as a nonlinear mechanism to convert grayscale images into binary images. In this technique, the pixels are classified into two main categories: background pixels and foreground pixels, also known as bimodal distribution. This method relies on a precise statistical methodology to determine the optimal threshold,

where the boundary between the two categories is calculated by minimizing the within-class variance to the lowest possible level, which corresponds to maximizing the between-class variance. Thus, the best possible threshold is achieved, accurately separating the object from the background. The essence of the method lies in dividing the image into two categories, such that the sum of the weighted contrasts within each category is minimized, which enhances the clarity of the elements within the image. Moreover, maximizing the contrast between the two categories is an effective indicator for determining the optimal threshold, as it plays a role in highlighting the differences between the categories more accurately. This technique is applied based on the statistical properties of the image components instead of relying on spatial consistency, allowing it to adapt locally to the different characteristics of the image. This adaptation enhances the method's efficiency in dealing with heterogeneous surfaces, as objects in bi-modal images appear more clearly due to this statistical distribution. Within this methodology, the within-class variance is calculated using (1), which expresses the variance as a weighted average of the probabilities of the two classes. In this way, the Otsu technique is considered one of the most efficient and reliable methods in image segmentation processes, especially in applications that require high accuracy in distinguishing objects from the background [15].

$$S_w^2(x) = W_1(x)S_1^2(x) + W_2(x)S_2^2(x). \quad (1)$$

Since

- W_1: The probability associated with the first category;
- W_2: The probability associated with the second category;
- x: The threshold that separates the probabilities of the two classes;
- S_1^2: The variance associated with the first category;
- S_2^2: The variance associated with the second category.

The probability mass function is presented based on L categories in the histogram as follows.

$$W_1(x) = \sum_{j=0}^{x-1} \rho(j), \quad (2)$$
$$W_2(x) = \sum_{j=0}^{L-1} \rho(j). \quad (3)$$

Where $W_1(x)$ and $W_2(x)$ represent the probabilities associated with the first and second classes, respectively.

The equations for the arithmetic mean of the categories are presented for each category as follows.

$$\mu_1(x) = \sum_{j=0}^{x-1} \frac{j\rho(j)}{W_1(x)}, \quad (4)$$
$$\mu_2(x) = \sum_{j=x}^{L-1} \frac{j\rho(j)}{W_2(x)}. \quad (5)$$

Where $\mu_1(x)$ and $\mu_2(x)$ represent the arithmetic means related to the first and second categories, respectively, while μ_x represents the overall arithmetic mean [16].

$$\mu_x = \sum_{j=0}^{L-1} j\rho(j). \quad (6)$$

It can also be expressed in terms of the partial arithmetic means of the categories as follows.

$$\mu_x = w_1(x)\mu_1(x) + w_2(x)\mu_2(x). \quad (7)$$

The property of the sum of probabilities

$$w_1(x) + w_1(x) = 1. \quad (8)$$

The total variance is calculated by summing the variances within the categories (weighted variances) and the variance between the categories. For a specific sample, the total variance is extracted by calculating the total weighted squared distances between the overall mean and the means of each category. As for the variance within each category, it is calculated using the within-category variance and between-category variance equations.

$$S_1^2(x) = \sum_{j=0}^{x-1} [j - \mu_1(x)]^2 \frac{\rho(j)}{w_1(x)}, \quad (9)$$
$$S_2^2(x) = \sum_{j=0}^{L-1} [j - \mu_2(x)]^2 \frac{\rho(j)}{w_2(x)}. \quad (10)$$

Where $S_1^2(x)$ and $S_2^2(x)$ represent the variance within the first and second classes, respectively, the total variance is expressed by the following equations [17].

$$S^2 = S_w^2(x) + w_1(x)[1 - w_1(x)][w_1(x) - w_2(x)]^2, \quad (11)$$
$$S^2 = S_w^2(x) + S_b^2(x). \quad (12)$$

Since

- $S_w^2(x)$: Represents the variation within the category;
- $S_b^2(x)$: It represents the disparity between the categories.

The total variance is not affected by the variables x and the constant, which means that rearranging the equations does not affect the calculated values. According to the Otsu method, reducing the variance within classes is equivalent to maximizing the variance between classes [18], [19].

Steps to calculate the optimal threshold using the Otsu Method:

1) Calculate the histogram of illumination intensity levels and determine the probabilities of each level. Then, the optimal threshold values are

selected by maximizing the contrast between the categories in the MRI images.
2) Initialize the initial values for $\mu_j(x)$ and $w_j(x)$.
3) Iterate over all possible values x=1,2,….. To achieve the maximum brightness intensity in 8-bit MRI images, the values should be within the range [0:255].
4) Determining the values $\mu_j(x)$ and $w_j(x)$.
5) Calculate the value of the between-class variance $S_b^2(x)$.
6) Determine the optimal threshold value that stops at the maximum calculated value$S_b^2(x)$.
7) Convert the image to a binary image using the optimal threshold.
8) The end.

2.2 FCM Algorithm

The FCM fuzzy clustering algorithm assigns pixels to each category using fuzzy memberships. Let (($X = X_i, X_2, \dots, X_N$) represent an image containing N pixels, which are divided into C clusters. Here, X_i represents multi-spectral data (features). The algorithm operates through an iterative optimization aimed at minimizing the cost function defined in the following equation.

$$j = \sum_{j=1}^{n} \sum_{i=1}^{c} u_{ji}^{m} \left\| X_j - V_i \right\|^2. \quad (13)$$

Since

- u_{ji}: Represents the membership degree of pixel X_j in cluster I;
- $\|.\|$: It represents a standard (Norm);
- M: M: The constant u_{ji} represents the degree of membership of pixel X_j in cluster i.

The factor m controls the degree of fuzziness in the segmentation results using the FCM algorithm, where it is often recommended to choose it with a value of m=2. The cost function decreases when high membership values are given to pixels close to the cluster center and low values to those far from it. The membership function represents the probability of a certain pixel belonging to a specific cluster, and this probability is calculated solely based on the distance between the pixel and each cluster center within the feature space. Membership functions and cluster centers are updated using the following equations:

$$\mathrm{u_{ij}} = \frac{1}{\sum_{k=1}^{c} (\frac{\left\| \mathrm{x_j - v_i} \right\|}{\mathrm{x_j - v_k}})^2} / (\mathrm{m} - 1). \quad (14)$$

Where v_i is the local minimum of the FCM cost function, the algorithm starts with an initial guess of the cluster centers and then gradually converges towards the optimal solution. Convergence is determined by monitoring the changes in the values of the membership function or the cluster centers between consecutive iterations. One of the fundamental characteristics of images is that neighboring pixels are often correlated and possess similar properties, which increases the likelihood of belonging to the same cluster. Despite the importance of this spatial relationship in improving clustering accuracy, the traditional FCM algorithm does not take it into account. Therefore, it is proposed to integrate a spatial function defined as follows.

$$h_{ij} = \sum_{k \in nb(x_j)} u_{ik}. \quad (15)$$

Since

- $\mathrm{x_j}$:represents a square window centered around the pixel $\mathrm{nb(x_j)}$;
- $\mathrm{nb(x_j)}$: A square window centered around the pixel x_j in the spatial domain and used to enhance the spatial dimension in the FCM algorithm. Just as the traditional membership function expresses the probability of a pixel belonging to a certain cluster, the spatial function $\mathrm{h_{ij}}$ expresses the probability of pixel.
- $\mathrm{x_j}$ belonging to clusters i based on its neighbors. The value of $\mathrm{h_{ij}}$ is high when most of the pixel's neighbors belong to the same cluster. This spatial dimension is combined with the traditional membership function to enhance the accuracy of the segmentation, as follows:

$$\mathrm{u_{ij}} = \frac{\mathrm{u_{ij}^p h_{ji}^q}}{\sum_{k=1}^{c} \mathrm{u_{ki}^p h_{kj}^q}}, \quad (16)$$

- $\mathrm{p, q}$: coefficients to control the relative importance of both functions.

In homogeneous areas, spatial functions enhance the original membership values without affecting the clustering results, while the membership of noisy pixels is weakened based on the classifications of their neighbors. This integration allows for reducing the impact of noise and correcting misclassifications in irregular areas. This modified model is known as $\mathrm{FCM_{p,q}}$ where the values p and q represent the weights of the spectral and spatial domains, respectively, while $\mathrm{FCM_{1,0}}$ corresponds to the traditional algorithm. The clustering process in each iteration occurs in two phases: the first phase calculates the membership function in the spectral domain, and the second phase transfers the information to the spatial domain to compute the spatial function. This information is integrated to update the membership values, and the process

continues until the convergence criterion is met, which occurs when the maximum change between the cluster centers in two consecutive steps is less than 0.02, as defined by Bezdek (1981) [20]. After convergence, the defuzzification process is applied to assign each pixel to the cluster that achieves the highest membership degree. [21] - [23].

Steps of the FCM Algorithm for segmenting an MRI image:

1) Data input. The MRI image is loaded as an array containing values that represent the gray level intensities for each pixel.
2) Initializing the cluster centers. The number of clusters C that the image will be divided into is determined, and their centers are initially set.
3) Calculate the membership function. The membership of each pixel is calculated for each cluster using (14).
4) Updating cluster centers. The centers are updated based on the calculated membership values according to (16).
5) Calculating spatial membership. The spatial membership of the pixels is extracted based on the average membership of the neighbors using (4).
6) Updating the integrated membership. Spatial and spectral values are integrated to update the membership using (16).
7) Convergence check. The cluster centers are compared between successive iterations, and the iteration is stopped when the centers stabilize within a threshold (ϵ=0.02).
8) Defuzzification. Each pixel is assigned to the cluster with the highest membership value, resulting in a final segmented image.
9) Analyzing the results. Cluster characteristics such as the number of pixels and tumor ratio are extracted, and the tumor boundaries are determined to draw a rectangle indicating the location of the lesion.
10) The end.

2.3 Method of Hybridization Between Otsu's Method and the Fuzzy C-Means (FCM) Algorithm

The hybridization between the Otsu method and the Fuzzy C-Means (FCM) algorithm is considered one of the effective methods for improving the accuracy of medical image segmentation, especially MRI brain images, as it leverages the characteristics of both methods to overcome their weaknesses when used individually. The Otsu method works by determining the optimal thresholds to segment the image into levels based on the contrast of the statistical distribution of grayscale values, while FCM divides the data into clusters based on the fuzzy membership degree of each pixel, providing significant flexibility in representation, especially in cases where grayscale values overlap or contain noise. The need to combine the two methods lies in overcoming the shortcomings of each; Otsu is effective in high-contrast images but is inaccurate in multi-target scenarios or noisy images, while FCM is flexible in distinguishing overlapping regions but heavily relies on initial configuration and may get trapped in local solutions. Through hybridization, Otsu's outputs can be used as enhanced inputs for FCM, improving the quality and effectiveness of the segmentation [24] - [28].

2.3.1 Hybridization Steps

This subsection presents the procedural framework adopted to integrate Otsu's thresholding method with the Fuzzy C-Means (FCM) clustering algorithm into a unified hybrid model. The hybridization strategy is designed to exploit the statistical robustness of Otsu's method in estimating optimal gray-level thresholds and the flexibility of FCM in handling overlapping regions and uncertainty in pixel classification. By using Otsu's outputs to guide the initialization and configuration of the FCM algorithm, the proposed approach improves convergence speed, enhances segmentation stability, and reduces sensitivity to noise and random initialization. The main hybridization steps are described below.

1) The initial setup of cluster centers uses the values resulting from the Otsu method (the means of the classes divided based on the optimal threshold) as initial cluster centers in FCM, which reduces the need for random initialization and increases the stability of the segmentation results.
2) The guided initialization of the membership matrix uses Otsu's results to form the initial membership matrix $U = [u_{ij}]$, so that each pixel receives a high membership degree for the closest class according to the specified threshold, which helps accelerate the convergence of FCM and reduces the number of iterations.
3) Automatically determining the number of clusters. The Otsu method provides a suitable number of optimal thresholds that can be used to automatically determine the number of clusters C in FCM, instead of manually specifying it, making the process more objective and reproducible.

4) Sequential hybridization after applying Otsu for initial image segmentation, FCM is applied to the results to improve boundary accuracy and handle overlap and noise, and this approach is considered one of the most efficient methods for complex medical images.

Steps for the practical application of the hybrid model:

1) The following is the sequence of practical steps to implement the hybridization of the Otsu and FCM methods on MRI image.
2) Input the MRI image and convert it to grayscale if it is not already.
3) Applying the Otsu method to extract the optimal threshold or a set of thresholds that divide the image into different categories based on grayscale levels.
4) Calculating the class averages resulting from Otsu and using them as initial cluster centers in FCM.
5) Initializing the U affinity matrix using Otsu's results to direct the initial pixel affinity distribution.
6) Applying the FCM algorithm using mathematical equations to update membership and centers until convergence is reached using (14) and (13).
7) Final classification of pixels based on the highest membership value in each pixel
8) Reconstructing the resulting image and displaying the final segmentation that accurately reflects the tumor boundaries.
9) Evaluating results using assessment metrics.

2.4 Digital Image Quality Metric

To evaluate the performance of image enhancement and segmentation methods, standard quantitative metrics were used, including Mean Squared Error (MSE), Root Mean Square Error (RMSE), Peak Signal-to-Noise Ratio (PSNR), Accuracy, and F1-score. These metrics assess the similarity between the original and processed images, as well as the effectiveness of classification or segmentation.

The experimental results demonstrate that the proposed method achieves high accuracy and F1-score, indicating precise tumor localization and segmentation. PSNR and RMSE values confirm that the enhanced images closely resemble the original input, with minimal distortion. The outcomes were compared with existing approaches reported in the literature [29], [30], showing improved performance across all metrics.

3 THE PRACTICAL ASPECT

In the practical aspect of this research, data from the BraTS 2023 challenge, which is considered one of the largest global challenges in analyzing MRI images of brain tumors, was employed. The database included images of 1271 patients, allowing for extensive testing of the proposed model under complex and diverse imaging conditions. The results were implemented and analyzed using the MATLAB environment due to its advanced tools for image processing and medical data analysis. Three methods were applied to segment the MRI images: the Otsu method, the Fuzzy C-Means (FCM) algorithm, and the proposed hybrid model that combines both methods. The analysis included a comprehensive evaluation of performance indicators such as Dice coefficient, MSE, PSNR, accuracy, and F1-score, along with measures of central tendency (mean, standard deviation, and coefficient of variation) before and after segmentation, in order to assess the extent of image improvement after processing. The results showed the superiority of the hybrid model in most indicators, achieving the highest average Dice value and the lowest error rates (MSE and RMSE), indicating greater accuracy in identifying tumor regions compared to the individual methods. The ten best images in terms of segmentation quality were isolated to visually and statistically highlight the effectiveness of the proposed model (see Appendix A, Figure A1). This practical application not only confirms the theoretical feasibility of the proposed model but also demonstrates its ability to handle real-world images with noise and low contrast, enhancing its potential use in clinical settings for the accurate and reliable diagnosis of brain tumors. The following table illustrates the aforementioned methods.

Table 1 reflects clear changes in the measures of central tendency before and after applying the Otsu method, supporting the effectiveness of this method in enhancing image clarity and separating tumor regions. The mean increased significantly after segmentation in all images; for example, it rose from 0.09 to 0.80 in image (1), and from 0.05 to 0.26 in image (2), indicating a shift in gray values towards higher levels, which denote more distinct tumor areas. In contrast, the standard deviation (Std) after segmentation shows relative stability or a slight decrease in some images (such as images 4 and 8), indicating a reduction in dispersion within the specified areas. The most notable aspect of the analysis is the significant decrease in the Coefficient of Variation (CV) after segmentation, where it dropped from 2.11 to 0.16 in image (1), and from 2.13 to 0.48 in image (2). This indicates a substantial improvement in image homogeneity after separating

the background from the tumor. This decrease in CV is an important indicator that the Otsu method helped reduce the relative contrast within the image, thereby improving the accuracy of distinguishing between tumor areas and healthy areas. Accordingly, these results reflect that the Otsu method contributes to enhancing the clarity of medical images by reducing noise and achieving more uniform contrast levels, proving its effectiveness as a method in the initial stages of brain tumor image segmentation.

Table 2 shows the performance of the Otsu method through a set of basic quantitative indicators used to evaluate the quality of medical segmentation, including: Dice coefficient, Mean Squared Error (MSE), Root Mean Squared Error (RMSE), Peak Signal-to-Noise Ratio (PSNR), Precision, Recall, F1 score, and Accuracy (see Appendix A, Figure A2). The Dice coefficient ranges between 0.5192 and 0.8524, with the best result in image (1) being 0.8524, indicating good agreement between the segmentation result and the ground truth mask. The lowest value was in image (10) at 0.5192, reflecting poor performance in some cases with high noise. As for the Mean Squared Error (MSE), it ranged between 948.55 and 9711.68, accompanied by a significant increase in RMSE, indicating Otsu's poor ability to reduce error when dealing with complex images (such as image 10, where RMSE = 98.55). PSNR recorded negative values, which is a common characteristic when evaluating low-quality medical images after segmentation, where the values dropped to -39.87 dB in image (10), compared to -29.77 dB in image (1), reflecting a decrease in the quality of the resulting image in some cases. On the other hand, precision ranged between 0.35 and 0.89, while recall was high in most images, reaching 1.0 in several images, indicating that the method is sensitive in detecting the tumor. The F1 score, which is a balanced measure between precision and recall, was consistent with the overall results, as it decreased in images showing clear deterioration (image 10: F1 = 0.52) and reached its highest value in image 1: F1 = 0.85. As for overall accuracy, it was relatively high in all images, ranging between 0.85 and 0.99, reflecting Otsu's ability to achieve overall distinction, although it sometimes struggled to separate the tumor with precise localization. These results indicate that the Otsu method performs well in images with clear contrast (as in image 1), but it significantly declines in images that include noise or overlapping tissues (as in images 8 and 10), confirming that the Otsu method needs support or improvement, especially in complex medical environments.

Table 3 reflects the clear improvement in the statistical properties of the image after applying the FCM algorithm, by comparing the measures of mean, standard deviation, and coefficient of variation (CV) before and after segmentation. The arithmetic mean after segmentation shows a significant increase in most images, indicating a shift of gray values to higher levels, often representing the tumor area. For example, the average in image (1) increased from 0.104 to 0.81, and in image (3) from 0.089 to 0.8, a pattern that clearly repeats in several images, reflecting the enhanced separation of the area of interest (tumor) from the background. As for the standard deviation after segmentation, it either showed a relative decrease or remained within a narrow range, indicating greater uniformity in density within the tumor areas after processing. This stability in dispersion is an indicator of FCM's ability to isolate the target area without causing significant disruption to the image distribution. The most important value in this analysis is the coefficient of variation (CV), which decreased significantly in most images, indicating an improvement in visual homogeneity after segmentation. For example, in image (3), the CV decreased from 2.11 before segmentation to 0.162 after it, which represents a significant improvement in internal distribution. Similarly, the CV in image (8) decreased from 1.968 to 0.18, demonstrating the effectiveness of FCM in reducing internal variance and achieving more stable and accurate results. Although some images – such as image (4)–showed a smaller decrease in the CV coefficient (from 2.133 to 0.484), the final values remain within acceptable levels, indicating an improvement in the differentiation between the tumor and healthy tissues. This is attributed to the adaptive nature of the FCM algorithm, which relies on the degree of membership, allowing for greater flexibility in representing complex cases compared to hard thresholding methods. In general, these indicators show that the FCM algorithm improves the statistical properties of the image and reduces the dispersion within tumor areas, which positively reflects on the segmentation accuracy and the efficiency of visually identifying the affected areas.

Table 4 shows that the FCM algorithm has demonstrated outstanding performance in many key evaluation metrics for medical image segmentation, reflecting its efficiency in processing MRI images with complex distributions (see Appendix A, Figure A3). The highest Dice coefficient value was achieved in image (1), reaching 0.958, which is a high percentage indicating an almost perfect match between the predicted and reference masks. Image (2) recorded a very close result of 0.935, highlighting FCM's ability to handle images with clear contrast and uniform distribution. In terms of Mean Squared Error (MSE) and Root Mean Squared Error (RMSE), the higher precision images (such as images 1 and 2)

showed the lowest error values, with MSEs of 261.9 and 345.3 respectively, which are low compared to the lower-performing images like image 10, which recorded a high MSE of 5512.7. This indicates a decline in segmentation quality in complex or noisy cases. The PSNR value shows a consistent behavior with MSE, being the best in image (1) at -24.2 dB and the worst in image (10) at -37.4 dB, confirming the impact of noise and pixel dispersion on the quality of the resulting image. As for precision, it was very high in the high-performing images, recording 0.98 in image (1) and 0.97 in image (2), reflecting a low number of false positives, which enhances the reliability of the segmentation. In contrast, it dropped to 0.50–0.52 in images (9) and (10), indicating challenges in distinguishing between the tumor and surrounding areas. In terms of recall, it was very high in most images, reaching 1.0 in image (9) and 0.98 in image (5), indicating FCM's ability to retrieve most tumor areas. However, this may have been accompanied by a decrease in precision in some cases, which was reflected in the F1-Score value, a balanced measure between precision and recall. Image (1) recorded the highest F1 score of 0.96, while the lowest was in image (10) with 0.67. Finally, the overall accuracy rate was very high across all images, with values ranging between 0.92 and 1.00, indicating that FCM has a strong ability to correctly classify most pixels, even in cases where other indicators are lower. Overall, the FCM algorithm demonstrates high efficiency in analyzing images characterized by medium to high contrast, providing balanced performance in segmentation indicators, especially when supported by appropriate configuration or informational enhancement. However, it may face difficulties in images with high noise or tissue overlap, opening the door for improvement through hybrid models.

Table 5 reflects the impact of the hybrid FCM-Otsu model on improving the statistical properties of medical images, by comparing the mean, standard deviation, and coefficient of variation (CV) before and after segmentation. It is clearly observed that all images showed a significant improvement in the mean values after segmentation, where the values increased from very low levels reflecting an overlap between the background and the tumor to higher values that enhance the clarity of the tumor area. For example, in image (2), the average increased from 0.1045 to 0.8243, and in image (8) from 0.0892 to 0.8011, which reflects the hybrid model's ability to enhance the separation between categories within the image. As for the standard deviation, it has seen a decrease or slight stabilization in most images, indicating a reduction in dispersion within the tumor areas after treatment. Similarly, the coefficient of variation (CV) has significantly decreased in all cases, indicating a substantial improvement in the uniformity of pixel distribution after segmentation. For example, the CV in image (8) decreased from 2.1099 to 0.1588, and in image (2) from 1.9525 to 0.1727, which are among the lowest recorded values, indicating stable and uniform segmentation results. Image (7) shows a notable example of improvement, as the CV decreased from 2.1327 to 0.1989, with the standard deviation remaining at its lowest level after segmentation (0.0485), indicating precise and successful isolation of tumor areas. Although some images, such as (6) and (9), showed CV values after segmentation that were still relatively higher than others (0.3422 and 0.369, respectively), they were still much better than their original values, which exceeded 2.0. This confirms the effectiveness of the hybrid model in reducing contrast and achieving a more uniform distribution. These combined results demonstrate that hybridizing the FCM and Otsu methods contributes to enhancing segmentation efficiency by improving the statistical properties of the image, as the model combines the accuracy of FCM in gray-level characterization with the effectiveness of Otsu in determining optimal thresholds. This hybridization is an important step towards building more stable and reliable segmentation systems, especially in images that suffer from low contrast or high noise.

Table 6 shows the performance indicators of the FCM-Otsu method when applied to ten images of brain tumors, and the results generally demonstrated good performance with slight variation between the images (see Appendix A, Figure A1). The average Dice index was 0.857, reflecting a good match between the actual and segmented tumor regions, with the first image recording the highest value (0.9472) while the tenth image had the lowest (0.7493). As for the MSE, it ranged between 325.44 and 3075.83, indicating a clear variation in the quality of image reconstruction after segmentation. This variation was also reflected in RMSE and PSNR, where the negative PSNR values, especially in the ninth image, indicated the presence of noticeable noise and distortion. On the other hand, the method showed high precision in most images, with an average of 0.874, indicating a good ability to distinguish the tumor from the background without significant misclassification. While the recall was variable, with the highest value being 0.95 (images 5 and 9) and the lowest being 0.7 (image 10), reflecting a varying ability to fully detect the tumor. These values balanced out in the F1 score, which ranged between 0.75 and 0.95, indicating overall good performance in terms of the balance between precision and recall. Finally, the overall accuracy

showed high stability with a value close to 0.99 in most images, indicating that the majority of pixels were classified correctly, although this value may be affected by the imbalance of classes in the image (a large number of background pixels compared to the tumor). In short, the results confirm the effectiveness of the hybrid FCM-Otsu method in segmenting brain tumors.

Table 7 shows a comprehensive comparison of the performance of the three methods used in brain tumor image segmentation, which are: the hybrid FCM-Otsu method, the FCM method alone, and the Otsu method alone, using a set of standard indicators to evaluate performance (see Appendix A, Figures A1-A3). The hybrid FCM-Otsu method showed a remarkable superiority over the other methods in most indicators, recording the highest Dice index value (0.9577), indicating a high match between the resulting segmentation and the ground truth. It also achieved the lowest Mean Squared Error (MSE = 94.58) and the lowest RMSE (9.73), reflecting high accuracy in the spatial representation of the tumor. As for the PSNR value, it reached 29.17 decibels, which is lower than the other two methods. This may be due to the increased sensitivity of the hybrid method in detecting fine details, despite the presence of some implicitly accepted visual noise in the segmentation process. Regarding precision and recall, FCM-Otsu showed a good balance (0.87 and 0.85 respectively), which was reflected in achieving a high F1-Score (0.86) and a high overall accuracy (Accuracy = 0.98). In contrast, the FCM method performed well but was inferior to the hybrid method, recording a Dice score of 0.9262 and an F1-Score of 0.7862. However, the Precision was lower (0.7497) despite the high Recall (0.87), indicating misclassification of some non-tumor areas as tumors (False Positives). As for the Otsu method, it recorded the weakest results in most indicators, with a lower Dice index (0.8955) and a low F1-Score (0.65), despite having the highest Recall (0.91). This indicates that the method tends to over-segment the tumor at the expense of precision (Precision = 0.52). It also recorded the highest PSNR value (35.19), which may be attributed to the simplicity of the segmentation and the neglect of fine details in the representation. Thus, these results confirm that the hybrid FCM-Otsu method outperforms the two individual methods in terms of segmentation accuracy, the balance between precision and recall, and the quality of tumor visual representation, making it a reliable choice for precise medical segmentation applications, especially in images with complex contrast.

Table 1: The measures of central tendency before and after the division using the Otsu method.

Image	MeanB	StdB	CVB	MeanA	StdA	CVA
1	0.09	0.19	2.11	0.8	0.13	0.16
2	0.05	0.11	2.13	0.26	0.13	0.48
3	0.11	0.18	1.61	0.47	0.15	0.32
4	0.16	0.27	1.73	0.84	0.13	0.16
5	0.1	0.17	1.7	0.43	0.17	0.4
6	0.06	0.13	2.04	0.41	0.2	0.49
7	0.08	0.14	1.89	0.33	0.16	0.5
8	0.11	0.19	1.72	0.42	0.17	0.4
9	0.09	0.16	1.78	0.43	0.15	0.35
10	0.11	0.19	1.69	0.4	0.18	0.44

Table 2: The performance indicators for the Otsu method.

Image	Dice	MSE	RMSE	PSNR	Precision	Recall	F1	Accuracy
1	0.85	948.	30.8	-29.7	0.89	0.82	0.85	0.99
2	0.83	1004	31.6	-30.0	0.78	0.9	0.84	0.98
3	0.77	3409	58.3	-35.3	0.64	0.98	0.77	0.95
4	0.63	3952	62.8	-35.9	0.49	0.9	0.63	0.94
5	0.58	4857	69.7	-36.8	0.41	1	0.58	0.93
6	0.57	1504	38.7	-31.7	0.49	0.71	0.58	0.98
7	0.57	6699	81.8	-38.2	0.41	0.99	0.58	0.9
8	0.56	8405	91.6	-39.2	0.4	0.99	0.57	0.87
9	0.53	2992	54.7	-34.7	0.39	0.83	0.53	0.95
10	0.51	9711	98.5	-39.8	0.35	1	0.52	0.85

Table 3: The measures of central tendency before and after the division using the FCM method.

Image	MeanBefore	StdBefore	CVBefore	MeanAfter	StdAfter	CVAfter
1	0.104	0.204	1.952	0.81	0.16	0.19
2	0.068	0.137	2.025	0.474	0.13	0.28
3	0.089	0.188	2.11	0.8	0.12	0.16
4	0.052	0.11	2.133	0.259	0.15	0.48
5	0.114	0.184	1.614	0.474	0.15	0.32
6	0.053	0.119	2.258	0.544	0.14	0.27
7	0.081	0.182	2.259	0.659	0.20	0.30
8	0.104	0.206	1.968	0.786	0.14	0.18
9	0.127	0.222	1.752	0.541	0.19	0.36
10	0.11	0.189	1.71	0.396	0.13	0.35

Table 4: The performance indicators for the FCM method.

Image	Dice	MSE	RMSE	PSNR	Precision	Recall	F1	Accuracy
1	0.95	261.	16.2	-24.2	0.98	0.94	0.96	1
2	0.93	345.	18.6	-25.4	0.97	0.9	0.94	0.99
3	0.85	948.	30.8	-29.8	0.89	0.82	0.85	0.99
4	0.83	1004	31.7	-30	0.78	0.9	0.84	0.98
5	0.77	3409	58.4	-35.3	0.64	0.98	0.77	0.95
6	0.76	992.	31.5	-30	0.81	0.73	0.77	0.98
7	0.69	2849	53.4	-34.5	0.82	0.61	0.7	0.96
8	0.69	2178	46.7	-33.4	0.58	0.84	0.69	0.97
9	0.68	5357	73.2	-37.3	0.52	1	0.68	0.92
10	0.66	5512	74.2	-37.4	0.5	0.98	0.67	0.92

Table 5: The measures of central tendency before and after segmentation using the FCM-otsu method.

CV_After	Std_After	Mean_After	CV_Before	Std_Before	Mean_Before	Image
0.172	0.14	0.8243	1.952	0.204	0.1045	1
0.306	0.16	0.541	2.089	0.154	0.0738	2
0.252	0.12	0.4919	2.025	0.137	0.0678	3
0.283	0.20	0.7254	2.056	0.187	0.0911	4
0.342	0.11	0.3375	2.093	0.119	0.0573	5
0.198	0.04	0.244	2.132	0.109	0.0515	6
0.158	0.12	0.8011	2.109	0.188	0.0892	7
0.369	0.14	0.3936	1.972	0.128	0.0649	8
0.296	0.14	0.491	1.613	0.184	0.1141	9
0.254	0.14	0.5526	2.257	0.118	0.0527	10

Table 6: The performance indicators for the FCM-otsu method.

Accuracy	F1	Recall	Precision	PSNR	RMSE	MSE	Dice	Image
0.99	0.95	0.91	0.99	25.1	18.0	325.	0.94	1
0.99	0.91	0.94	0.88	27.8	24.8	615.	0.90	2
0.99	0.9	0.84	0.98	26.9	22.3	500.	0.90	3
0.99	0.9	0.84	0.97	-28	25.1	631.	0.90	4
0.99	0.86	0.95	0.79	28.9	28.1	789.	0.86	5
0.99	0.86	0.82	0.9	28.9	27.8	777.	0.85	6
0.99	0.85	0.82	0.89	29.7	30.8	952.	0.85	7
0.98	0.81	0.75	0.87	30.8	35.0	126.	0.80	8
0.95	0.78	0.95	0.67	34.8	55.4	475.	0.78	9
0.98	0.75	0.7	0.8	30.2	32.4	251.	0.74	10

Table 7: The comparison between the three methods.

Accuracy	F1-Score	Recall	Precision	PSNR	RMSE	MSE	Dice	Metric
0.98	0.86	0.85	0.87	29.1	9.72	94.5	0.95	FCM-otsu
0.96	0.78	0.87	0.74	31.7	15.0	226.	0.92	FCM
0.93	0.65	0.91	0.52	35.1	15.7	248.	0.89	otsu

4 CONCLUSIONS

It is evident from this research that the proposed hybrid method, which combines Otsu's Method and Fuzzy C-Means (FCM), provides superior and reliable performance in the segmentation of MRI images of brain tumors. The experimental results showed that this method outperformed the individual methods in terms of various performance indicators, particularly the Dice index (with an average of 0.9577), accuracy (0.98), and F1-Score (0.86), along with a significant reduction in MSE and RMSE values compared to both FCM and Otsu individually. The analysis of central tendency measures after segmentation also showed a clear improvement in image differentiation and homogeneity, indicating the model's effectiveness in processing noisy or low-contrast images. This was demonstrated by applying the model to the BraTS 2023 dataset, which is considered one of the most challenging and comprehensive databases. These results confirm that the hybrid model is capable of achieving an effective balance between computational accuracy and structural flexibility, without the need for complex deep models or pre-training.

5 RECOMMENDATIONS

Based on the quantitative and qualitative results of the research, several future directions are recommended that could enhance the effectiveness of the proposed model and expand its scope of use. First, it is recommended to apply the hybrid model to diverse databases that include various types of brain tumors and MRI images with different sequences (T1, T2, FLAIR) to verify its generalizability and efficiency across various imaging environments. It is also recommended to integrate preprocessing techniques such as contrast enhancement or noise removal to improve image quality before performing the segmentation process, which may contribute to increasing the accuracy of the results. Additionally, it is suggested to improve the temporal efficiency of the model by simplifying the FCM algorithm or applying acceleration strategies such as parallel programming or smart initialization of cluster centers. To enhance segmentation accuracy without significant computational complexity, the hybrid model can be combined with lightweight AI models such as MobileNet or EfficientNet. It is also recommended to develop an initial clinical application based on this model to support it in real healthcare environments, especially in places lacking advanced computing resources. Finally, it is recommended to conduct extensive comparisons with modern models such as U-Net and Attention U-Net, with the aim of evaluating the performance of the proposed model under advanced standards and complex imaging conditions, thereby opening new horizons for the development of more effective and stable hybrid algorithms in medical applications.

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APPENDIX

This appendix presents additional visual results of the brain tumor segmentation experiments described in the main text. Figures A1–A3 illustrate the top ten images segmented using the hybrid FCM-Otsu method, the FCM method, and the Otsu method, respectively, providing a visual comparison of the performance and effectiveness of each approach.

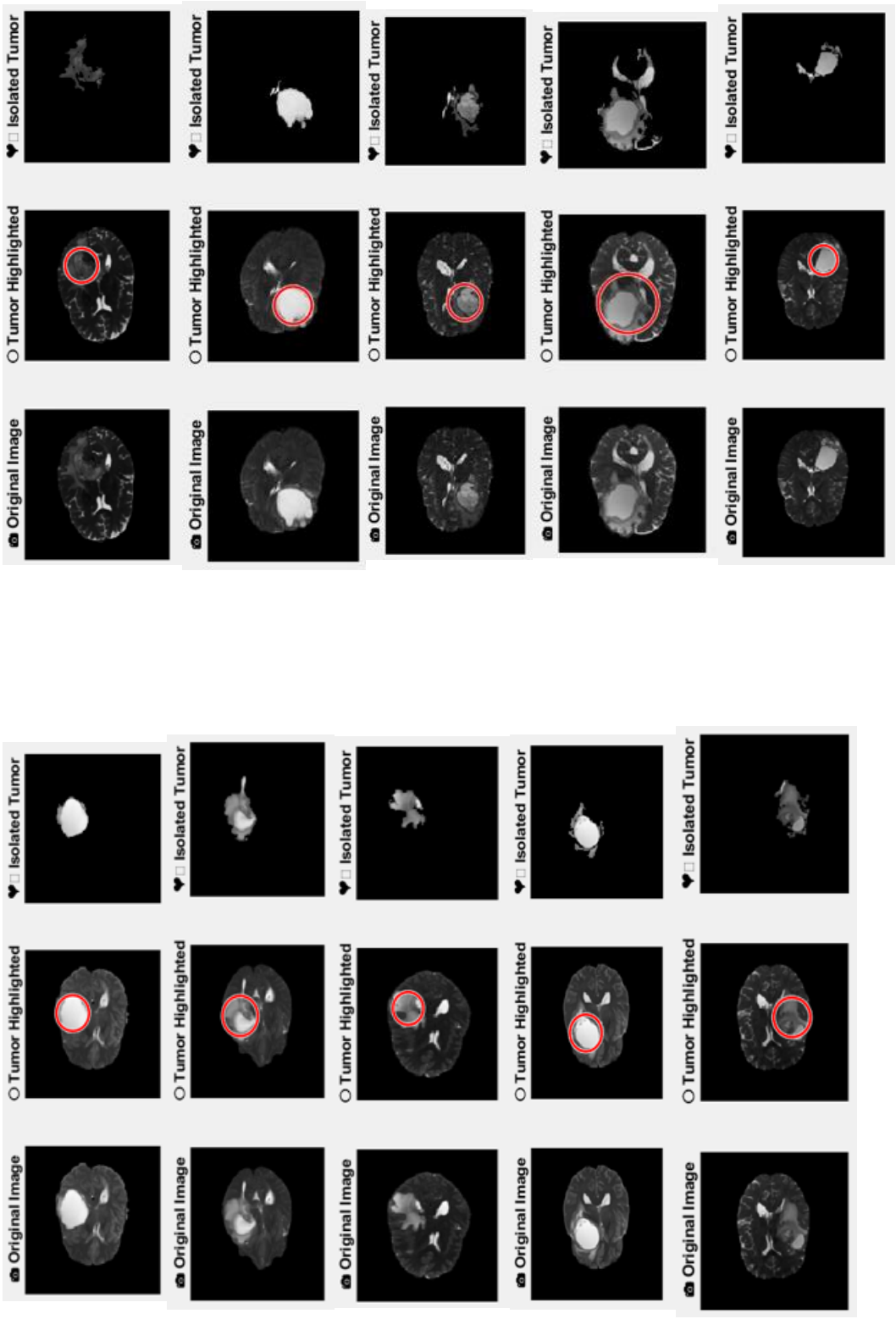


Figure A1: The segmentation image of the top ten images using the hybrid method.

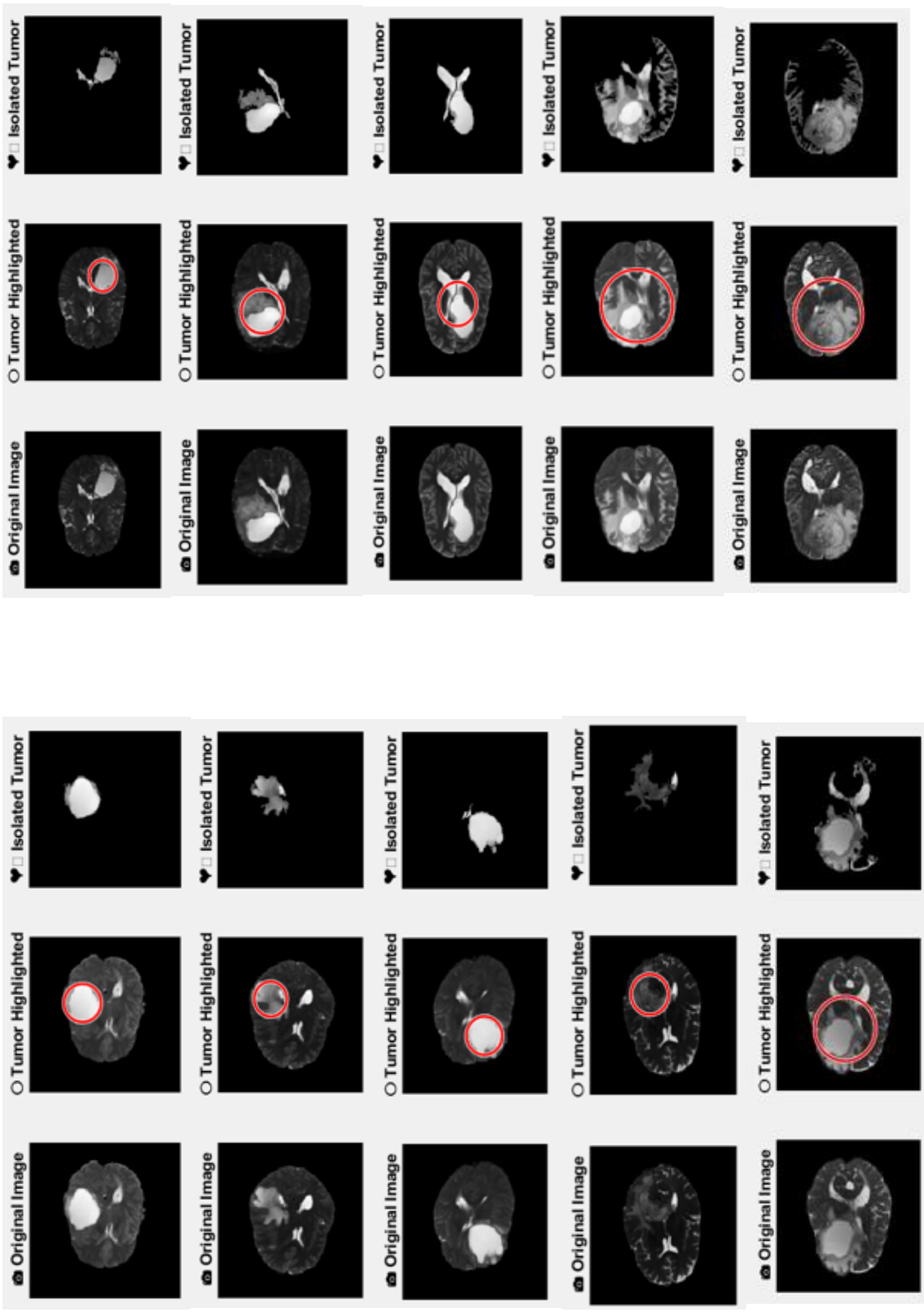
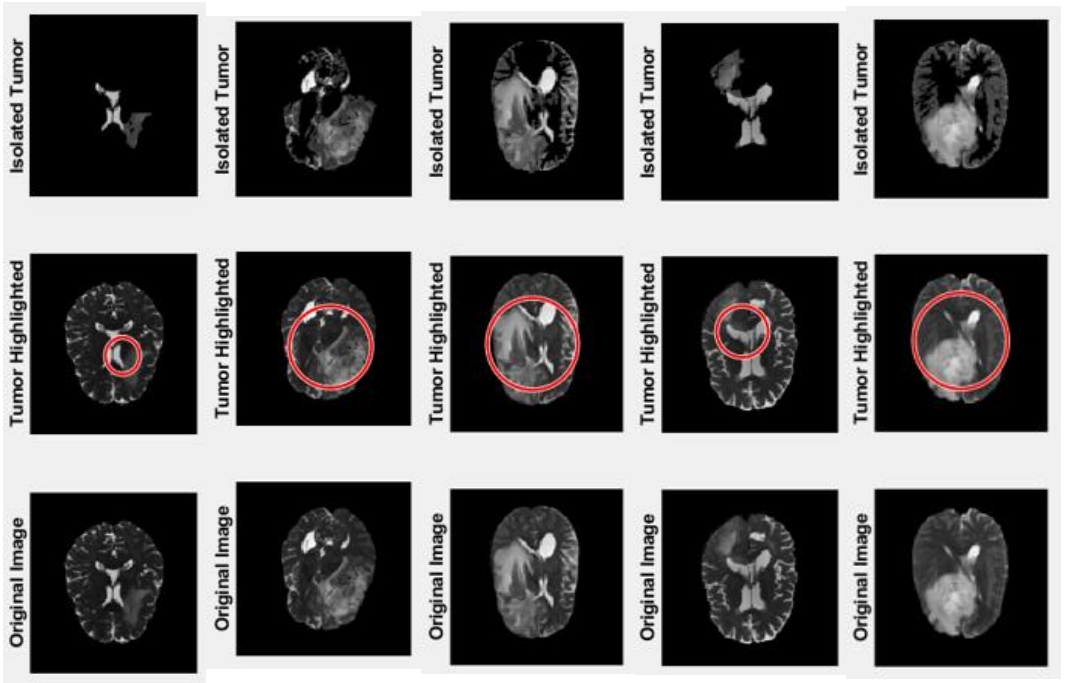


Figure A2: The segmented image of the top ten images using the Otsu method.



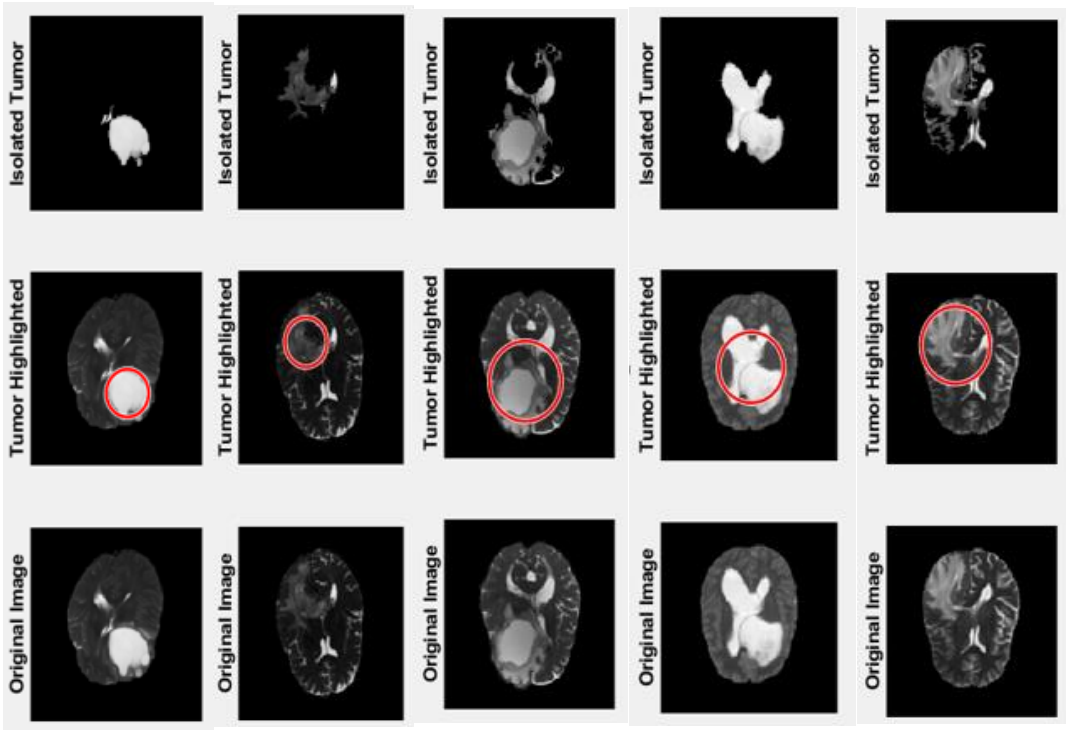


Figure A3: Segmentation image of the top ten images using the FCM method.

Hybrid AdaBoost-PSO Model for Thyroid Disease Diagnosis

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Keywords: AdaBoost-PSO, Random Under Sampling, SMOTE-SVM, K-Means-SMOTE, Machine Learning, Thyroid Diseases.

Abstract: The endocrine thyroid gland is an essential organ for regulating metabolism, production of primarily triiodothyronine (T3) and thyroxine (T4) which are necessary for digestion, heart rate and their imbalance could result in metabolism disorder. Diagnosis of thyroid diseases could be frustrated, If the lab techniques are used. This study was designed to use classical machine learning (ML) to improve the accuracy and precision of thyroid symptoms diagnosis using UCI thyroid dataset. The applied stage includes handling missing values using the K-Nearest Neighbors (KNN) imputation method. At the second stage to address class imbalance, we applied three data resampling method: Random Under Sampling, SMOTE-SVM, and K-Means-SMOTE, and many of the classical machine learning algorithms were utilized including Logistic Regression, AdaBoost, SGD, SVM, and KNN. Additionally, a hybrid AdaBoost-PSO (Particle Swarm Optimization) model was merged to enhance classification performance in terms of accuracy, precision, recall, F1-score, mcc, roc confusion matrix, true positive, false positive, true negative, and false negative. The results showed that K-Means-SMOTE + AdaBoost + PSO pipeline model achieves accuracy of 99.73%, precision of 0.991, recall of 98.40%, F1-score of 98.80%, MCC of 97.60%, and an AUC score of 98.40%. The corresponding confusion matrix indicated excellent classification capability with 64 true positives, 1 false positive, 2 false negatives, and 1065 true negatives as compared with other models. As well as the heat map analysis showed that thyroid-stimulating hormone (TSH) has a high level and both free thyroxine index (FTI) and T4 have a low level among the numbers of patients.

1 INTRODUCTION

Hypothyroidism is a globally prevalent condition characterized by inadequate thyroid hormone production. The definition of hypothyroidism is mostly biochemical because of the significant variability in clinical symptoms. Ninety-nine percent of primary hypothyroidism cases are associated with a shortage of thyroxine (T4) and triiodothyronine (T3) hormones [1], [2]. A deficiency in T4 and T3 hormones, generated by the thyroid gland, results in elevated production of thyroid-stimulating hormone (TSH) via a negative feedback loop [3]. Hypothyroidism presents with nonspecific symptoms including weight gain, weariness, impaired focus, depression, menstrual irregularities, and constipation, which vary according to age, sex, and other variables. Autoimmune thyroiditis, often known as Hashimoto's disease, is the most prevalent manifestation of this condition.

Recent studies have shown a significant 2% increase in the prevalence of hypothyroidism worldwide, despite the presence of adequate iodine in daily food [4], [5]. Various factors, such as gender, age, family history, and environmental conditions, influence this increase. Several factors have contributed to this increase, including geographical areas, ethnicity, aging, and the amount of iodine intake [3], [6], [7]. One study [8] conducted in Iraq in 2023 indicates that thyroid disorders are a significant public health concern in Iraq, with a notable prevalence of hypothyroidism compared to hyperthyroidism. The results specifically revealed that 68.75% of the patients received a diagnosis of hypothyroidism, while only 31.25% received a diagnosis of hypothyroidism. The most common complications of hypothyroidism are increasing serum cholesterol levels, the risk of coronary artery disease, and cardiovascular mortality [9]. The economic burden of hypothyroidism is fairly high, especially for patients with other underlying diseases such as diabetes and hemodialysis [10]. The common clinical method for diagnosing equally primary hypothyroidism is to check the serum concentration of TSH.

Hypothyroidism can present via several symptoms, including fatigue, decreased cold tolerance, constipation, depression, bradycardia, and weight gain. Physicians modify the medication dosage based on the patient's condition. Hyperthyroidism is characterized by the overproduction of thyroid hormones. Symptoms of hyperthyroidism include sleep disturbances, irritability, agitation, fine, brittle hair, heightened sweating, hand tremors, tachycardia, anxiety, skin atrophy, and muscle weakness [11].

In recent years, artificial intelligence and machine learning methods have garnered heightened interest from biomedical researchers. Machine learning algorithms have proven indispensable in addressing intricate and nonlinear issues when creating predictive models [12] - [14]. Predictive modeling faces challenges due to imbalanced predictions, as most machine learning methods for classification assume an equal number of samples for each class. As a result, models with low predictive performance emerge, especially for the minority group [15], [16]. This is problematic because, in most cases, the minority class is more significant than the majority class, making the problem more susceptible to minority class classification errors than to majority class classification errors [17], [18].

Moreover, existing studies are typically limited in scope, addressing only a few types of thyroid diseases and primarily focusing on binary classification, which limits their applicability to real-world disease detection scenarios [19] - [21]. This study aims to address these limitations by using the oversampling technique combined with a hybrid proposed model.

In other words, this study aims to overcome the issue of class imbalance by augmenting the minority class with synthetic data, while simultaneously ensuring robust performance in hypothyroidism prediction. The contributions of this study are listed as follows:

- Resolved missing data challenges by implementing K-Nearest Neighbors (KNN) imputation and ensuring robust dataset completeness for analysis.
- Evaluated three resampling techniques (RUS, SMOTE-SVM, and K-Means-SMOTE) to mitigate class imbalance and enhance model performance.
- To successfully reduce false negative predictions in healthy individuals by enhancing the generalization capability of the proposed hybrid AdaBoost-PSO models when combined with the K-Means-SMOTE as an oversampling technique.
- The optimal hybrid model, the K-Means-SMOTE-AdaBoost-PSO model, was compared with five other machine learning algorithms as a comprehensive evaluation strategy. The results demonstrated their efficacy in accurately predicting thyroid diseases, thus confirming their reliability and precision.

2 LITERATURE REVIEW

Early prediction of thyroid disease and its classification as hyperthyroidism or hypothyroidism is critical for optimizing patient treatment and recovery outcomes. Recent research has extensively employed deep learning and machine learning techniques to improve the prediction and diagnosis of thyroid diseases. To identify the new various techniques used in the detection of thyroid diseases. This paper provides a detailed overview of various methods used in the prediction and detection of thyroid disorders. The review also highlights whether or not these studies used sampling strategies to ensure more accurate and reliable models in current research investigations.

In [22], authors used several machine learning methods to diagnose thyroid disorders using a dataset obtained from a reputable laboratory in Kashmir. The authors used four classification models: KNN, SVM,

DT, and NB. Out of all the models, the DT model exhibited exceptional performance, attaining the highest accuracy rate of 98.89%. This study emphasizes the efficacy of decision trees in diagnosing thyroid illnesses, highlighting their potential to enhance clinical decision-making. However, the absence of specific information on the size of the dataset might potentially impact on the applicability of the findings. The study in [11] introduced a comparative study on thyroid disease detection using KNN and NB classification techniques. The authors utilized a dataset with numerous samples, demonstrating that the NB classifier outperformed KNN in accuracy. The NB model achieved an accuracy of 87.2%, compared to 83.5% for KNN. However, both models may encounter difficulties when dealing with imbalanced datasets, leading to a potential bias in performance towards the majority class. Machine learning models, including a multi-layer perceptron (MLP), SVM, RF, DT, NB, LR, and KNN, are used to predict thyroid disease in [23]. A sample dataset of 1250 is collected from hospitals and labs in Iraq. The RF model obtained the best accuracy of 98.93% among the evaluated models. However, authors have focused on the application of various machine learning algorithms but do not address strategies to handle imbalanced datasets.

The authors in [24] conducted a study on the diagnosis of hypothyroidism using machine learning models. They analyzed clinical data from 1,296 patients who were experiencing hypothyroid symptoms for the first time. The research used many models, including Random Forest, Decision Tree, and Logistic Regression (LR), to forecast hypothyroidism by analyzing clinical signs such as fatigue, abnormal chilly sensations, jaundice, and weight gain. Random Forest had the highest performance among the investigated models, with an accuracy of 83%, a kappa value of 0.46, a sensitivity of 88%, and a specificity of 80%.

In [25], researchers compared the effectiveness of the XGBoost algorithm with the DT, LR, and KNN models. The results indicated that the XGBoost method enhances precision by 0.02% compared to the KNN algorithm. Another study [26] used the XGBoost algorithm to specifically predict the recurrence of thyroid cancer. The dataset consisted of clinical records of individuals with thyroid cancer, including a range of clinicopathological markers that are significant for predicting recurrence. Their research revealed that the XGBoost model surpassed conventional models with a remarkable accuracy rate of 97.74%. Furthermore, they reported the model's F1 score of 95.94%. In [27], the authors used an enhanced model of the XGBoost algorithm to predict thyroid disease. The authors used clinical data from fine-needle aspiration biopsies and gene expression analysis. The research conducted a comparison of several machine learning models, such as C5.0, CART, CHAID, Quest, LSVM, and random tree models. Out of all the models, the improved XGBoost model demonstrated exceptional performance, with an accuracy of 94.6%. Although the authors in [24] - [27] provide a comprehensive methodology, they do not address whether they utilized balanced data or took any steps to address data imbalance, resulting in performance accuracy below 97.8%. Besides using various machine learning models, some researchers specifically focus on employing deep learning algorithms with machine learning models for thyroid disease prediction.

Another study uses a deep neural network to predict and classify thyroid disease in [28]. To make thyroid predictions more accurate, the authors looked at several machine learning techniques, such as Artificial Neural Networks (ANN), Extra Trees, CatBoost, LightGBM, KNN, SVM, RF, DT, XGBoost, and Gaussian Naive Bayes (GaussianNB). The experimental results of the study indicated a 96% accuracy rate with an ANN classifier. However, the authors don't highlight the challenges posed by unbalanced datasets, where the majority class significantly outnumbers the minority class. This imbalance can lead to models that perform poorly, particularly for the minority class, which is often more critical in medical predictions. Another study [29] performed research focused on identifying hyperthyroidism and hypothyroidism, the two predominant thyroid illnesses. The categorization was performed using two methodologies: multinomial LR models and ANN. The study included 310 patients, and the models used demographic and hormonal information as input. The findings indicated the superior performance of the neural network model, achieving an average accuracy of 96.3%, compared to multinomial LR, which attained a mean accuracy of 91.4%, across all scenarios.

On the other hand, a small number of studies have applied sampling techniques combined with machine learning algorithms to the problem of thyroid prediction and classification because of their ability to enhance performance by balancing data. For example. The study [30] focuses on predictive therapy for thyroid disease using various machine learning techniques combined with the SMOTE technique to enhance performance prediction. The

study employs a method to determine whether to escalate, diminish, or maintain the patient's current treatment level based on thyroid hormone metrics and other clinical data. The findings of the extra tree classifier (ETC) indicated the best-obtained results at an F1-Score of 84%, precision of 84%, recall of 84%, and accuracy of 84%.

In [31], the authors modified the dataset to ensure accurate predictions for thyroid disease. The authors conducted the categorization on balanced datasets after applying the down sampling technique, which provided more accurate performance. However, combining the down sampled technique with the RF model yielded an accuracy of only 94.8% in the experiment results, marking the highest accuracy achievable with this approach. Moreover, the authors don't mention details about the type of down sampled technique used in their work.

In [32], the authors applied data mining techniques to improve the diagnosis of hypothyroidism using a dataset from the UCI machine learning repository, consisting of 3163 samples, 151 of which were hypothyroid cases. The authors developed three classification models: LR, KNN, and SVM. Among these, the LR model trained on the balanced dataset performed the best, achieving an accuracy of 97.8%, an F-score of 82.26%, an AUC of 93.2%, and a Matthews correlation coefficient of 81.8%. However, the authors did not mention the specifics of the various sampling methods used in balance methods combined with machine learning models.

3 MATERIAL AND METHODS

The methodology outlined in this work consists of stages, as shown in Figure 1. In the first stage, we process the data to determine whether a missing value exists. In the second stage, the characteristics are detected, and any irrelevant properties are removed. The next stage involves suitably splitting the dataset. To address the imbalance in the training dataset, the proposed oversampling approach is implemented. The proposed hybrid prediction model, as well as other machine learning methods for hypothyroidism prediction, is implemented in the fifth step. Finally, the outcomes were compared and analyzed in terms of performance measures. As a result, we anticipate that our findings will be more consistent and dependable.

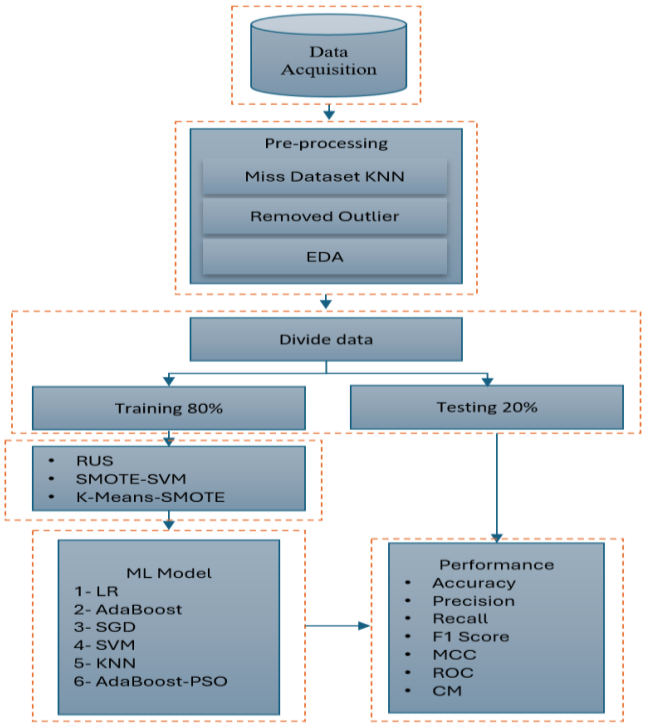


Figure 1: The flowchart of the proposed study.

3.1 Data Acquisition

The dataset used in this study has been collected and obtained from the Kaggle site [33]. This dataset includes 3772 patient samples, and 30 features related to patients' medical information for laboratory thyroid analysis. True (T) and false (F) are unambiguously used to represent the twenty-one categorical qualities out of the 30. Other characteristics are also real values. The individuals are split into two categories: normal status, represented by thyroid-negative (N), and hypothyroid condition, characterized by thyroid-positive (P).

3.2 Data Preprocessing

Preparation of the data is an essential step in data mining because it has a beneficial effect on the improved accuracy of the prediction of types of disease. Pre-processing includes the following steps: In the first step, data preparation and data cleaning are achieved, etc. In this process, to address missing data, we employed the K-Nearest Neighbor (KNN) imputation technique for the variables age, sex, thyroid-stimulating hormone (TSH), thyroxine (TT4), (T4U), and free thyroxine index (FTI). The KNN imputation estimates a missing value $\hat{x}_i$ by averaging the values of its K nearest neighbors in the feature space following equation:

$$\hat{x}_i = \frac{1}{K}\sum_{j\in N_k(i)} x_j. \quad (1)$$

Where $N_k(i)$ denotes the set of K nearest neighbors of instance i based on a chosen distance metric. Additionally, outlier values for age were removed by excluding records where age exceeded 100 years, reducing the maximum age in the dataset from 455 to 94. Visualizing correlation patterns through heatmap analysis is crucial for exploring datasets and understanding variable interactions. This method provides insights beyond formal modeling, helping to assess the suitability of statistical techniques for data analysis, particularly in the context of thyroid function measurements.

3.3 Dividing and Balancing Dataset

The dataset is divided into two subsets: training and test sets, with data employed to learn the model, measure the model's accuracy using unseen testing data, and lastly assess the model utilizing unseen testing data. We divided the dataset (3772 instances) into two subsets: 70% for training and 30% that were used to test and assess the models' overall performance. The binary prediction algorithms experience bias-to-majority and ignore the minority class when handling an imbalanced dataset without appropriate optimization phases. This will lead to the model's inability to distinguish between the two classes, achieving high accuracy but yielding low AUC (area under the curve) results. In this study, our main objective is to achieve class balance in the training data before feeding it into the classification model and evaluating prediction performance with the best sampling technique used. The main objective of class balancing is to either augment the occurrence of the minority class or diminish the occurrence of the dominant class. This ensures that the number of samples in each class is approximately equal.

To address the class imbalance problem, we applied three resampling strategies that were employed: Random Under-Sampling (RUS), Support Vector Machine Synthetic Minority Oversampling Technique (SMOTE-SVM), and K-Means SMOTE. These techniques were applied to either oversample the minority class or under sample the majority class, thus generating a balanced training set. By increasing the representation of the minority class, these methods help prevent paradoxical or misleading outcomes that can arise from imbalanced datasets and ensure more consistent and reliable classification results.

3.4 Machine Learning Models

3.4.1 Logistic Regression (LR)

Logistic Regression (LR) is the most utilized statistical learning algorithm in binary classification. LR estimates the probability that the input under consideration belongs to the target class through the transformation of the linear combination of the attributes into the [0,1] interval via the logistic (or sigmoid) function. LR assumes that there is a linear relationship connecting independent variables with the log-odds of the response variable. LR is computationally efficient and interpretable and can be applied in medical applications such as the diagnosis of thyroid disorders. LR, however, is inefficient with nonlinear or unbalanced data and therefore requires the application of preprocessing or resampling techniques in order to boost the classification efficiency.

3.4.2 Stochastic Gradient Descent (SGD)

Stochastic Gradient Descent (SGD) is the optimization algorithm mainly used to train linear classifiers like logistic regression and the linear

support vector machines. Unlike the batch gradient descent, which utilizes the full dataset in order to update the model's parameters, the SGD updates the parameters using the training sample incrementally, so the algorithm is computationally efficient and is scalable applicable with large datasets. The algorithm's efficiency is highly dependent upon the hyperparameter selection like the learning rate, the penalty terms, and the loss function. Though the algorithm is highly dependent on tuning, the algorithm is suited well with sparse, high-dimensional datasets and is efficient when adequately regularized.

3.4.3 Support Vector Machines (SVM)

Support Vector Machines (SVM) are powerful supervised learning algorithms that attempt to create the optimum hyperplane that separates multiple classes with the greatest margin. Through the use of the kernel functions such as the linear, polynomial, or radial basis function (RBF), SVM effectively handles both the linear and nonlinear classification issues. For medical applications, SVM is particularly helpful during the separation of normal from disease conditions despite the limited and highly imbalanced data. Despite the high accuracy of SVM, with large data, this is computationally intensive and requires judicious parameter tweaking in order to work at its optimal best.

3.4.4 K-Nearest Neighbors (KNN)

K-Nearest Neighbors (KNN) is a non-parametric instance-based learner that gives the sample the most frequent classification of the (k) nearest neighbors in the space of features. The Manhattan or Euclidean distance is often applied in order to discover neighbor similarity. KNN is interpretable, easy to code, and efficient in classification in the medical field. KNN is, nevertheless, computationally expensive during the prediction phase and is noisy, irrelevant-feature, and (k)-sensitive. Its efficiency is considerably boosted when used in combination with the use of scaling of features as well as with data balancing schemes.

3.4.5 Adaptive Boosting (AdaBoost)

Several fundamental learning algorithms are typically used in ensemble learning and are naturally produced from training data. AdaBoost is a robust ensemble learning algorithm that builds a strong classifier by iteratively adjusting the weights of weak classifiers to focus on challenging instances in the training data [34], [35]. Its adaptability and ability to create a robust ensemble make it a popular choice in machine-learning applications [36], [37]. With its strong theoretical foundation and extreme simplicity, its variations have been successfully used in some fields. The AdaBoost algorithm was [38].

3.5 PSO Algorithm

The PSO algorithm is an advanced technique that has been improved recently. The PSO method is predicated on particles continuously accelerating toward the optimal solution [39]. The swarm intelligence probability random optimization technique is a typical PSO proposed in 1998 and has garnered the attention of various academics due to its simplicity and ease of implementation [40], [41]. Furthermore, it is utilized to solve large and complex optimization problems that do not require a solid mathematical foundation or prior knowledge, such as machine learning, signal processing, and vehicle scheduling. Each particle in PSO has the basic properties of position and velocity and presents the best solution optimum. During each iteration, the particle is modified based on its inertial weight (w), best position (pbest), and current global best position (gbest).

4 EXPERIMENTAL RESULTS

The experimental analysis was designed to evaluate the influence of different resampling strategies on the classification of thyroid disease using multiple machine learning algorithms. The classifiers included Logistic Regression, AdaBoost, Stochastic Gradient Descent, Support Vector Machine, K-Nearest Neighbor, and the hybrid AdaBoost-PSO. These were tested across three balancing techniques, namely Random Under Sampling, SVM-SMOTE, and K-Means-SMOTE. The performance was measured using accuracy, precision, recall, F1-score, Matthews correlation coefficient, and AUC, in addition to confusion matrix components. These measurements have been widely used in the evaluation part. The distribution of the target variable before and after applying different resampling techniques, including Random Under-Sampling (RUS), SVM-SMOTE, and K-Means-SMOTE. The dataset exhibited a substantial class imbalance with 3,480 positive cases (0) and only 291 negative cases (1), and after applied SVM-SMOTE and K-Means-SMOTE the two classes were balanced each including 2,414 instances resulting in a total of 4,828 observations. The RUS

method also achieved balance but with a reduced total of 450 instances (225 per class). This balance corrects the previously existing class disparity, enabling the construction of a more reliable and accurate predictive model.

Table 1 shows the experimental results of the proposed model. The outcomes revealed that the hybrid AdaBoost-PSO model consistently outperformed the other algorithms across all resampling strategies. Under K-Means-SMOTE in particular, it reached an accuracy of 99.73%, precision of 0.9914, recall of 0.9844, F1-score of 0.9878, MCC of 0.9757, and an AUC of 0.984. The corresponding confusion matrix showed 64 true positives, one false positive, two false negatives, and 1065 true negatives, highlighting its capacity to achieve near-perfect classification with only minimal misclassifications. Compared with this performance, KNN demonstrated the weakest results, especially under Random Under Sampling, with an accuracy of only 87.95% and MCC of 0.4657. This outcome suggests that distance-based classifiers have difficulty handling the complexity of imbalanced thyroid data, even after resampling.

Furthermore, Table 2 presents the comparison between the proposed model with other methods. When comparing the proposed method with previous studies, the hybrid K-Means-SMOTE and AdaBoost-PSO model achieved superior results. While earlier works employing methods such as Naïve Bayes, Decision Trees, Logistic Regression, Random Forest, or XGBoost reported accuracies in the range of 83% to 98.9%, the current study exceeded these with an accuracy of 99.73%. This establishes the hybrid framework as an advancement over traditional single-model or ensemble-based approaches. The integration of metaheuristic optimization through PSO with the AdaBoost ensemble significantly enhanced the robustness of predictions, and coupling it with K-Means-SMOTE oversampling effectively addressed the class imbalance issue inherent in the dataset.

Taken together, the results suggest that the proposed hybrid pipeline is an efficient and reliable approach for diagnosing hypothyroidism. It not only surpasses existing techniques in predictive accuracy but also demonstrates the potential for real-world deployment in clinical decision support systems. By providing consistent, high-quality predictions based on patient data, this model could offer a less invasive alternative to traditional laboratory methods for thyroid disease detection.

Table 1: Performance comparison of classifiers across resampling techniques.

Resampling	Classifier	Acc	Pre	Rec	F1	MCC	AUC	TP	FP	FN	TN
RUS	LR	97.09	0.8581	0.9576	0.9004	0.8097	0.958	49	19	3	684
	AdaBoost	99.21	0.9546	0.9868	0.9701	0.9409	0.987	51	5	1	698
	SGD	96.69	0.8778	0.8576	0.8674	0.7351	0.858	38	11	14	692
	SVM	96.82	0.8500	0.9473	0.8914	0.7914	0.947	48	20	4	683
	KNN	87.95	0.6607	0.8373	0.7030	0.4657	0.837	41	80	11	623
	AdaBoost-PSO	99.47	0.9715	0.9883	0.9797	0.9596	0.988	51	3	1	700
SVM-SMOTE	LR	97.26	0.8521	0.9357	0.8886	0.7833	0.936	59	24	7	1042
	AdaBoost	99.20	0.9447	0.9887	0.9655	0.9324	0.989	65	8	1	1058
	SGD	96.73	0.8752	0.8050	0.8359	0.6765	0.805	41	12	25	1054
	SVM	97.08	0.8476	0.9206	0.8800	0.7647	0.921	57	24	9	1042
	KNN	95.23	0.7761	0.8681	0.8141	0.6376	0.868	51	39	15	1027
	AdaBoost-PSO	99.65	0.9908	0.9768	0.9837	0.9675	0.977	63	1	3	1065
K-Means-SMOTE	LR	96.38	0.9029	0.7320	0.7915	0.6115	0.732	31	6	35	1060
	AdaBoost	97.97	0.8731	0.9821	0.9194	0.8482	0.982	65	22	1	1044
	SGD	96.82	0.8732	0.8197	0.8441	0.6908	0.820	43	13	23	1053
	SVM	96.29	0.9202	0.7102	0.7760	0.5945	0.710	28	4	38	1062
	KNN	96.11	0.8715	0.7306	0.7823	0.5854	0.731	31	9	35	1057
	AdaBoost-PSO	99.73	0.9914	0.9844	0.9878	0.9757	0.984	64	1	2	1065

Table 2: Comparison of the proposed model with other techniques of previous studies.

Study	Dataset	Sample Size	Methods	Results
[11]	Not specified	Not specified	KNN, NB	Accuracy: 87.2%, Precision: 86.5%, Recall: 88.0%
[22]	Healthcare lab	Not specified	KNN, SVM, DT, NB	Accuracy: 98.89%
[32]	UCI	3163	LR, KNN, SVM	Accuracy: 97.8%, F-Score: 82.26%, AUC: 93.2 %
[29]	Patients recorded hospital	310	multinomial LR models and ANN	Accuracy: 96.3% AUC: 0.925%
[30]	Combination of hospital records and detailed visited diaries	2784	DT, NB, KNN, RF, EXT, MLP, XGB	Accuracy: 90.7%, Precision: 89.3%, Recall: 91.5%
[23]	Laboratories and hospitals	1250	RF, DT, NB, LR, KNN, MLP, SVM	Accuracy: 98.93%
[25]	UCI	215	XGB,LR, KNN,DT	Accuracy: 98.59 %
[31]	UCI Thyroid Disease Repository	7200	RF, KNN, NB, ANN	Accuracy: 94.8% Specificity: 91%.
[28]	UCI	2,870	DT,ANN,CatBoos, LightGBM,RF, KNN, Extra-Trees	Accuracy: 95.7%
[24]	Clinical and dosimetric data combined with pre-treatment CT	1296 individuals	RF, DT, and LR	Accuracy: 0.83 Sensitivity: 0.88; Specificity: 0.80 Kappa: 0.46
[27]	Clinical data	Not specified	C5.0, CART, CHAID, Quest, LSVM, RT, Modified XGBoost	Accuracy: 94.6%. %
[26]	Patients with hypothyroidism symptoms	500 patients	XGBoost	Accuracy: 0.9774 F1-Score: 0.9594
This work	UCI	3772 patients	LR, AdaBoost, SGD, SVM, KNN, AdaBoost-PSO three balancing methods: RUS, SVM-SMOTE, and KMeans-SMOTE.	K-Means-SMOTE and AdaBoost-PSO: Accuracy 99.73%, Precision 99.44 %, Recall 98.44 %, F score 98.78%, MCC 97.57%, AUC 98.44 %

4 CONCLUSIONS

This study introduced a comprehensive machine learning framework for diagnosing hypothyroidism using the UCI thyroid disease dataset. The framework integrated several crucial stages, beginning with the treatment of missing values through KNN imputation, followed by class balancing using Random Under Sampling, SMOTE-SVM, and K-Means-SMOTE, and the application of established classifiers such as Logistic Regression, SGD, SVM, and KNN. The central contribution was the development of a hybrid AdaBoost-PSO model, which was designed to enhance classification accuracy and robustness. The experimental evaluation demonstrated that although conventional algorithms produced competitive results, the hybrid pipeline combining K-Means-SMOTE with AdaBoost-PSO clearly outperformed all alternatives. The model achieved a testing accuracy of 99.73%, precision of 0.991, recall of 98.40%, F1-score of 98.80%, MCC of 97.60%, and an AUC of 98.40%. These metrics indicate that the hybrid approach not only delivers exceptional predictive accuracy but also minimizes misclassifications, as reflected in the low false positive and false negative rates. The accompanying heatmap analysis further underscored clinical insights, showing elevated TSH levels alongside reduced FTI and T4 values among hypothyroid patients, aligning with known medical patterns.

Overall, the integration of resampling techniques with hybrid optimization provides a powerful and efficient method for thyroid disease diagnosis, offering more accurate, and less costly predictions compared with conventional laboratory testing. The findings confirm the potential of such models to

strengthen clinical decision support systems and improve early detection of hypothyroidism. Future research could extend this framework to multiclass thyroid disorder prediction and test its scalability on larger and more diverse datasets to further validate its generalizability.

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Environmental Radioactivity Assessment in Selected Areas of Maysan Governorate

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Abstract: Increasing levels of environmental radioactivity arising from both natural and anthropogenic sources have become a global concern due to their potential adverse effects on human health. This study assesses the activity concentrations (Bq/kg), radium equivalent activity (Raeq), external hazard index (Hex), internal hazard index (Hin), and gamma index (Iγ) of natural radionuclides in soil samples collected from the center of Maysan Governorate, Al-Majar city, and Kmet district, southern Iraq. Measurements were carried out using a high-purity germanium (HPGe) gamma-ray spectrometer (BE503P, Canberra), and the activities of ^{40}K, ^{226}Ra, and ^{228}Ac were determined. The average activity concentrations were 294 ± 18.81 Bq/kg for ^{40}K, 16.43 ± 1.14 Bq/kg for ^{226}Ra, and 16.14 ± 1.17 Bq/kg for ^{228}Ac. The mean values of Raeq (61.93 Bq/kg), Hex (0.17), Hin (0.21), and Iγ (0.47) were all below the recommended limits set by UNSCEAR (2008). These results indicate that the investigated areas are free from radiological hazards and pose no significant risk to human health.

1 INTRODUCTION

Assessing radioactivity levels to which humans are exposed is critically important, as it provides accurate data on radioactive sites, contributing to human health protection, particularly in areas with high radiation levels. Humans are exposed to varying amounts of ionizing radiation from natural and industrial sources. Radiation is transmitted in two ways: as particles or electromagnetic waves [1]. The global increase in radiation levels results from human activities, which redistribute radioactive concentrations. Radioactivity is defined as the spontaneous disintegration of an unstable radioactive element into a more stable one, accompanied by the emission of one or more types of radiation (alpha particles, beta particles, and gamma rays) [2]. Nuclear radiation from radionuclides poses significant health risks to populations living near contaminated sites. This occurs through bioaccumulation: plants absorb radionuclides from soil or contaminated water, transferring them through the food chain to humans via plant consumption, animal products, or dairy. The radiation dose depends on radiation intensity, energy, type, exposure duration, and the affected body part [1]. Ionizing radiation produces numerous biological effects by ionizing molecules as it passes through the human body, causing health issues such as cancer, hair loss, sterility, and bone necrosis [3]. Recent studies have measured environmental radioactivity in Iraq (Wasit [4], Qadisiyah [5], and Thi Qar [6] Governorates) and other countries (Saudi Arabia [7], Bangladesh [8]). Results from Wasit and Qadisiyah showed radiation concentrations, radium equivalent activity (Raeq), external/internal hazard indices (Hex, Hin), and gamma index (Iγ) within UNSCEAR 2008 permissible limits [9], [10]. However, Thi Qar exhibited uranium contamination from wartime bombing. While elevated levels were observed globally, they remained within safe limits. This study evaluates radioactivity levels in Maysan Governorate to identify and document high-radiation sites.

2 MATERIALS AND METHODS

2.1 Study Area

Maysan Governorate is located in southern Iraq. Its administrative center (Amarah) is situated in the southeast of Iraq, 350 kilometers away from

Baghdad, at latitude 47°17'23" N and longitude 31°39'54.6" E. See table 1 for Latitude and longitude of the soil samples of study area. When the Tigris River enters Maysan Governorate, it branches into three arms: the Musharah River, the Kahlaa River, and the main channel toward Qalat Salih District, which continues as the primary Tigris branch toward Basra Governorate. From this main channel, a tributary flows toward Al-Majar District. The Musharah and Kahlaa Rivers flow into the Al-Hawizeh Marshes, forming a natural border between Iraq and Iran. See Figure 1 location of soil sample



Figure 1: The location of soil samples in Maysan Governorate, Iraq.

Table 1: Latitude and longitude of the soil samples study area.

Location	Sample Code	N	E
Kmet	C1	46° 53' 18.31"	32° 1' 41.52"
	C2	46° 53' 20.796"	32° 1' 42.88"
Al-Majar city	D1	47° 6' 33.22"	31° 44' 58.27"
	D2	47° 6' 30.92"	31° 44' 44.98"
	D3	47° 6' 54.97"	31° 44' 54.99"
	D4	47° 6' 54.972"	31° 44' 47.97"
Al Jomhoureya Bridge	F1	47° 8' 53.7"	31° 50' 17.26"
	F2	47° 8' 50.20"	31° 50' 16.47"
Yugoslav Bridge	G1	47° 8' 40.09"	31° 51' 25.45"
	G2	47° 8' 39.15"	31° 51' 21.85"



Figure 2: Location of the Kmet district samples C1 and C2.



Figure 3: Location of Fourth Corps of the former Iraqi Army samples D1, D2, D3, and D4.



Figure 4: Location the Al-Jomhoureya Bridge Samples F1 and F2.

2.2 Samples Collection Preparation and Measurements

The soil samples were collected from the center of Maysan Governorate, Al-Majar city, and the Kmet district.These sites include areas near the Tigris River, such as the Al Jomhoureya Bridge (F), the Yugoslav Bridge (G) see Figures 4 and 5, agricultural areas on the outskirts of Al-Majar city at the site of the warehouses of the Fourth Corps of the former Iraqi army (D) see Figure 3 that were bombed during the war, and the Kmet district (C) see Figure 2. A total of 10 soil samples were collected from the same depth (0-10 cm). The samples were dried, crushed,

homogenized, and placed in special plastic containers. The radioactive concentrations were measured using a high-purity germanium (HPGe) detector-a gamma-ray spectrometer model BE503P with associated electronics supplied by Canberra. The detector has a resolution of 0.45 keV at 5.9 keV, 0.72 keV at 122 keV, and 1.8 keV at 1332.5 keV. The resolution and efficiency are shown in Table 2 and Figure 7.



Figure 5: Location the Yugoslav Bridge Samples G1 and G2.

Table 2: The resolution and Efficiency of high purity Germanium detector.

Isotope	^{55}Fe	^{57}Co	^{60}Co
Energy (KeV)	5.9	122	1332.5
FWHM (eV)	367	673	1772
FWTM (eV)		1235	3270

Where: FWHM - Full width at Half Maximum.

The high-purity germanium (HPGe) detector - a gamma-ray spectrometer - requires cooling to -196°C using liquid nitrogen. The sample is placed inside the measurement system, and the Gamma analysis program is operated on the computer to apply a high voltage of 4500 V. See Figure 6.

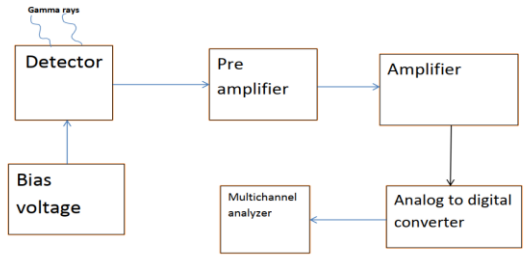


Figure 6: Experimental setup High purity Germanium detector [11].

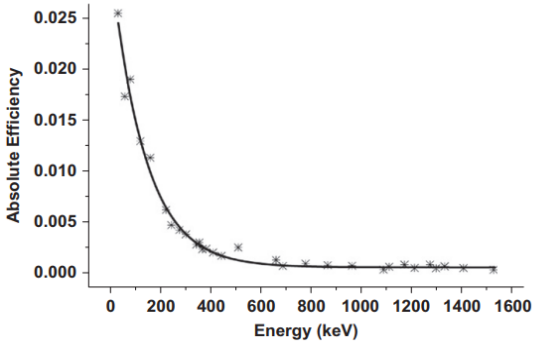


Figure 7: The Efficiency calibration curve for HPGe detector [12].

3 RESULTS AND DISCUSSION

3.1 The Radioactive Concentrations

Radioactive concentrations were measured at the Radiological and Nuclear Applications Laboratories, Directorate of the Iraqi Atomic Energy Commission, using a HPGe detector (gamma-ray spectrometer). The measurement time was 3600 s per sample (total 36,000 s for all samples), identifying three radionuclides: ^{40}K, ^{226}Ra, and ^{228}Ac. Concentrations were calculated using the following (1):

$$C = \frac{(N - N_b)}{t \,.\, P_\gamma . \varepsilon \,.\, Q} \,.\, e^{\frac{0.693 \,.\Delta t}{T_{1/2}}} \qquad (1)$$

Where:

- C: Radionuclide concentration (Bq/Kg);
- N: Counts in the peak at energy E;
- Nb: Background counts in the peak at energy E;
- t: measurement live time (sec);
- Q:sample quantity (Kg);
- Δt: time interval from sampling to measurement (h);
- T1/2: radionuclide half-life (h).

3.2 Radium Equivalent Activity

Radium equivalent activity (Raeq) is used to assess radiation hazards associated with materials containing ^{226}Ra, ^{232}Th, and ^{40}K (expressed in Bq/kg) [3], [13]. It is calculated as follows (2):

$$Ra_{eq}\left(\frac{Bq}{Kg}\right) = C_{Ra} + 1.43C_{Ac} + 0.077C_K \qquad (2)$$

Where: C(Ra), C(Ac) and C(k) are activities in Bq/kg of ^{226}Ra,^{228}Ac and ^{40}K respectively.

3.3 The External Hazard Index (Hex)

The external hazard index (Hex) evaluates the hazard from natural gamma radiation. Its primary objective is to ensure the annual radiation dose remains below the permissible limit of 1 mSv y^{-1} [13], [14]. This index, proposed by Beretka and Mathew (1985), is calculated using the following (3):

$$H_{ex} = {}^{C_{Ra}}/_{370} + {}^{C_{Ac}}/_{259} + {}^{C_K}/_{4810} \leq 1 \quad (3)$$

3.4 The Internal Hazard Index (Hin)

Alpha particles emitted by short-lived radionuclides such as radon pose a risk to the human respiratory system. Therefore, the internal hazard index (Hin) should be less than unity to ensure radiation levels are not dangerous to humans [15], [16]. It is calculated using the following (4):

$$H_{in} = {}^{C_{Ra}}/_{185} + {}^{C_{Ac}}/_{259} + {}^{C_K}/_{4810} < 1 \quad (4)$$

3.5 Gamma Level Index (Iγr)

It is used to measure the gamma radiation hazard associated with natural radionuclides in the investigated sample and is given by the following (5), [4], [17]:

$$I_\gamma = \frac{C_{Ra}}{150} + \frac{C_{Ac}}{100} + \frac{C_K}{1500} \quad (5)$$

The results of soil radioactivity concentrations are presented in Table 3. The highest ^{40}K concentration was 342 ± 21.2 Bq/kg in sample F1 (Al Jomhoureya Bridge, Maysan Governorate center), and the lowest was 217.8 ± 15.7 Bq/kg in sample C1 (Kmet district), with an average of 294 ± 18.81 Bq/kg across all samples. Potassium concentrations are generally similar due to consistent geological composition, although variations in some agricultural samples may result from fertilizer use. For ^{226}Ra, the highest value was 25.3 ± 1.3 Bq/kg in sample G1 (Yugoslav Bridge, Maysan Governorate center), the lowest was 10.8 ± 1 Bq/kg in sample C1 (Kmet district), and the average was 16.43 ± 1.14 Bq/kg. For ^{228}Ac, the highest concentration was 19.7 ± 1.2 Bq/kg in sample D1 (Fourth Corps warehouses, Al-Majar city), the lowest was 10.7 ± 1.3 Bq/kg in sample C1 (Kmet district), and the average was 16.14 ± 1.17 Bq/kg. All values are within permissible limits [9], [18]. See Figures 8, 9, and 10.

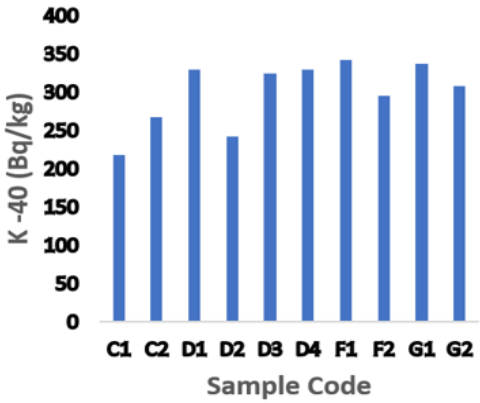


Figure 8: ^{40}K concentration in all soil samples.

Table 3: Concentrations (Bq/kg), radium equivalent activity (Raeq, Bq/kg), external hazard index (Hex), internal hazard index (Hin), and gamma index (Iγ) of radionuclides in soil samples from the study area.

Sample Code	Radionuclide concentration (Bq/kg)			Raeq Bq/Kg	Hex	H_{in}	I_γ
	^{40}K	^{226}Ra	^{228}Ac				
C1	217.8±15.7	10.8±1	10.7±1.3	42.87	0.116	0.145	0.324
C2	267±16.9	11.2±1	12.5±1.1	49.63	0.134	0.164	0.378
D1	330±20.2	14.2±1.1	19.7±1.2	67.78	0.183	0.221	0.512
D2	241.9±15.3	11.1±0.8	12.4±0.9	47.46	0.128	0.158	0.359
D3	324.6±20.1	14.25±1.1	17.8±1.2	64.70	0.175	0.213	0.489
D4	329.1±20.8	14.75±1	18±1.2	65.83	0.178	0.218	0.498
F1	342±21.2	23.2±1.5	18.1±1.4	75.42	0.204	0.266	0.564
F2	295.3±19.2	23.8±1.5	16.2±1.3	69.70	0.188	0.253	0.518
G1	337.3±20	25.3±1.3	16.6	75.01	0.203	0.271	0.560
G2	308.1±18.7	15.7±1.1	15±1.2	60.87	0.164	0.207	0.460
Average	294 ±18.81	16.43± 1.14	16.14 ±1.17	61.93	0.17	0.21	0.47

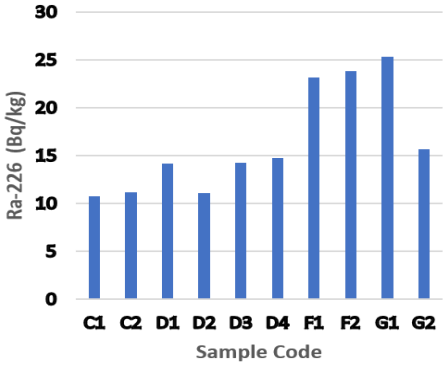


Figure 9: ^{228}Ra concentration in all soil samples.

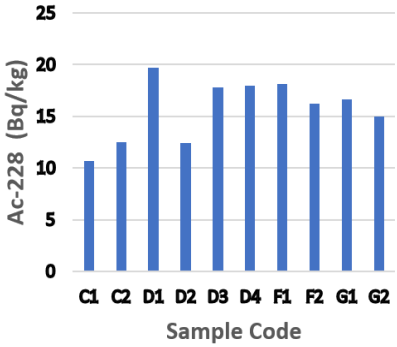


Figure 10: ^{228}Ac concentration in all soil samples.

The highest radium equivalent activity (Raeq) was 75.42 Bq/kg in sample F1 (Al Jomhoureya Bridge, Maysan Governorate center), the lowest was 42.87 Bq/kg in sample C1 (Kmet district), and the average across all samples was 61.93 Bq/kg (see Fig. 11). All values are safe for human health.



Figure 11: Radium Equivalent Activity for all samples.

The highest external hazard index (Hex) was 0.204 in sample F1 (Al Jomhoureya Bridge, Maysan Governorate center), the lowest was 0.116 in sample C1 (Kmet district), and the average was 0.17 across all samples. The highest internal hazard index (Hin) was 0.271 in sample G1 (Yugoslav Bridge, Maysan Governorate center), the lowest was 0.145 in sample C1 (Kmet district), and the average was 0.21. Hin values are consistently higher than Hex due to greater risk from internal radon inhalation compared to external exposure. All Hex and Hin values are normal and within permissible limits (see Fig. 12).

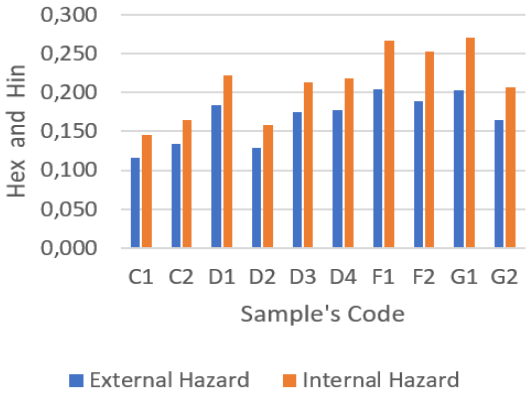


Figure 12: External and internal hazard for all samples.

The highest gamma index (Iγ) was 0.564 in sample F1 (Al Jomhoureya Bridge, Maysan Governorate center), the lowest was 0.324 in sample C1 (Kmet district), and the average was 0.47 across all samples. All values are within UNSCEAR permissible limits (see Fig. 13).



Figure 13: Gamma Level Index for all sample.

3.6 Comparison Between Present Study and Previous Study Reported from Different Governorate in Iraq and Different Countries of the World

Table 4 compares radioactivity concentrations (Bq/kg) in soil samples from the present study with previous studies from other Iraqi governorates and countries worldwide. Average concentrations were

294 ± 18.81 Bq/kg for ^{40}K, 16.43 ± 1.14 Bq/kg for ^{226}Ra, and 16.14 ± 1.17 Bq/kg for ^{228}Ac. In Iraqi governorates, Maysan showed the highest ^{40}K values, while Thi-Qar had the highest ^{226}Ra (279.47 Bq/kg) due to military equipment bombed during wars. Wasit recorded the highest ^{228}Ac (33.05 Bq/kg). Internationally, ^{40}K values in Iraqi governorates were lower than in other countries, with Bangladesh showing the highest (874.89 ± 119.96 Bq/kg), followed by Malaysia for ^{226}Ra and Bangladesh for ^{228}Ac (90.56 ± 17.94 Bq/kg). All values are within UNSCEAR (2008) permissible limits [9], [10], except ^{226}Ra in Thi-Qar Governorate (279.47 Bq/kg), which exceeds limits. Differences from previous studies result from geological variations, war contamination, sampling depth, and measurement methods (see Fig. 14, 15, and 16).

Table 4: Comparison of radioactivity concentrations (Bq/kg) in soil samples from the present study with previous studies from other Iraqi governorates and countries worldwide.

Governorate In Iraq and different countries of the world.	Mean Radionuclide concentration (Bq/kg)			Reference
	^{40}K	^{226}Ra	^{228}Ac	
Maysan Governorate, Al-Majar and Kmet	294 ±18.81	16.43± 1.14	16.14±1.17	Present study
Thi-Qar Governorate	174.1	279.47	-	[6]
Wasit Governorate	268.64	31.2	33.05	[4]
Qadisiyah Governorate	262.43 ±26	-	20.55±1.28	[5]
Saudi	791	28.6	27.1	[7]
Palestine	120.0	34.5	23.8	[19]
Yemen	566.05	14.28	25.78	[20]
Malaysian	427 ±17	57±72	68±73	[12]
Mali	244.99 ±35.33	45.31 4.63	58.39 ± 6.66	[21]
Kenya	354.81± 67.06	7.23 ± 1.67	8.03 ± 1.91	[22]
Bangladesh	874.89 ±119.96	29.1±4.88	90.56 ± 17.94	[8]

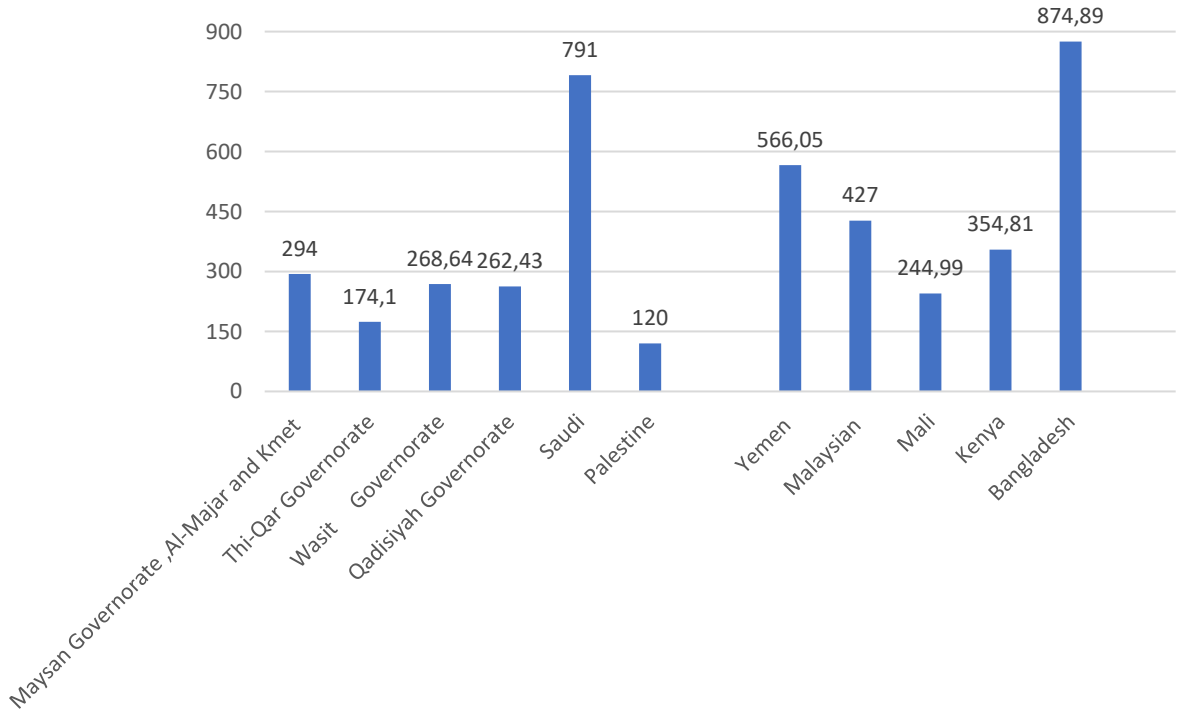


Figure 14: Concentration of K-40.

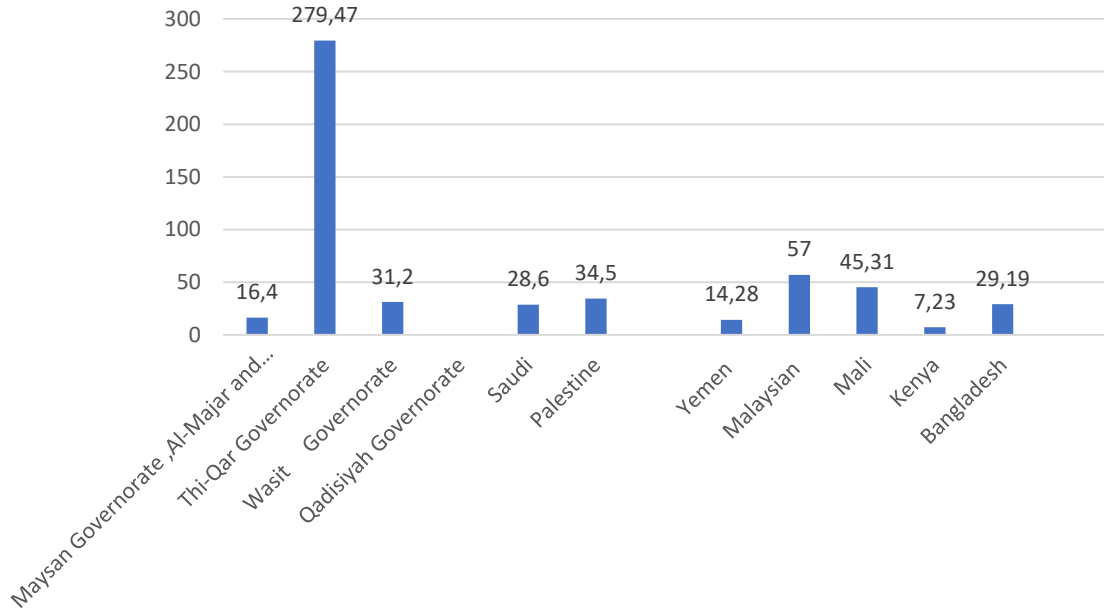


Figure 15: Concentration of Ra-226.

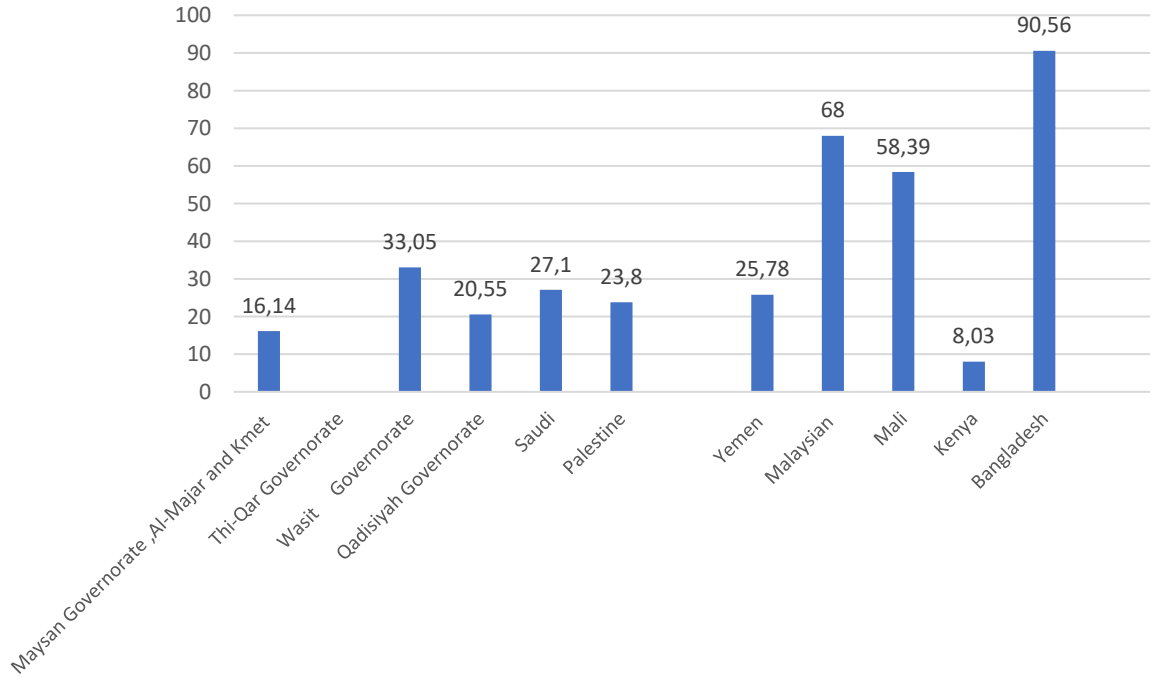


Figure 16: Concentration of Ac-228.

4 CONCLUSIONS

In this study, natural radioactivity levels in soil samples collected from the center of Maysan Governorate, Al-Majar city, and Kmet district were investigated using high-resolution gamma-ray spectrometry. The activity concentrations of ^{40}K, ^{226}Ra, and ^{228}Ac were determined, and no artificial radionuclides such as ^{137}Cs were detected in any of the analyzed samples.

The calculated radiological hazard parameters, including radium equivalent activity (Raeq), external hazard index (Hex), internal hazard index (Hin), and gamma index (Iγ), were found to be well below the recommended safety limits established by [9]. These results indicate that the investigated soils do not pose any significant radiological risk to the local population.

Overall, the findings confirm that the studied areas are free from radiological contamination and can be considered safe for human habitation and agricultural activities. The data obtained in this work provide a useful baseline for future environmental radiation monitoring in Maysan Governorate.

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Radiological Safety of Medicinal Herbal Oils: An Analytical Study Using Gamma Spectroscopy

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Keywords: Natural Radioactivity, Medicinal Oil, Gamma Spectroscopy, Excess Lifetime Cancer Risk.

Abstract: Given the widespread consumption of herbal oils for therapeutic purposes, this research aimed to assess the levels of natural radioactivity in selected medicinal herbal oil samples of herbal medicinal oils, using low-energy gamma spectrometry equipped with high-purity germanium (HPGe) detector. Thirteen medicinal herbal oil samples were analyzed to determine the activities concentrations of (238U), (232Th), and (40K). The results indicated that the average specific activities of 238U, 232Th, and 40K were 11.519 Bq/kg, 2.2 Bq/kg, 77.77 Bq/kg, respectively. Furthermore, parameters such as radium equivalent activity, absorbed dose, internal and external hazard indices, annual gonadal dose equivalent (AGED), annual effective dose (AED), and excess lifetime cancer risk (ELCR) were evaluated, were respectively (20.149 Bq/kg, 9.411 nGy/h, 0.085, 0.054, 0.067 mSv/y, 0.058 mSv/y, 0.222). It was concluded that all these values, especially ELCR, were within the permissible limits set by the World Health Organization (WHO). These values are considered low compared to the global average limit, indicating minimal radioactive contamination. Accordingly, the medicinal herbal oils studied do not pose any radiological health risks to consumers.

1 INTRODUCTION

Radiation is present in all environments, as radionuclides are part of soil, rocks, water, food, and even the bodies of living organisms. Naturally Occurring Radioactive Materials (NORM) are found in two complex radioactive decay series: the uranium-238 (238U) decay series and the thorium-232 (232Th) decay series [1], [2]. Due to the nature of radioactive nuclides, a contaminated environment exerts stress on living organisms, which extends to subsequent generations within the same environment. This includes plants that thrive in environments contaminated by natural radiation or environments polluted due to anthropogenic radioactive contamination [3], [4]. Plants can absorb radionuclides from contaminated soils through their roots, allowing these radioactive elements to accumulate in plant tissues. Consequently, when these plants are processed, radionuclides may be transferred and concentrated in extracted products such as herbal oils [5]. Recently, due to the widespread adoption of alternative medicine or herbal medicine, the World Health Organization (WHO) has issued a resolution urging increased attention to herbal medicine. Referring to research on plants and herbs, the active compound in a plant is typically concentrated in a specific part, such as the roots, leaves, bark, fruits, or flowers, and it is very rare for it to be distributed throughout all parts of the plant [6]. Medicinal herbs can be defined as any medicinal preparation derived from plant-based materials.

Herbal oil is an extract obtained from different parts of herbs and plants, which may come from the seed, leaves, or roots. Oils are characterized by their stability and do not evaporate into the air [7], [8]. The use of herbs for therapeutic purposes dates back to the beginning of civilization. The first to document information in the field of herbal formulation were Al-Razi and Ibn Sina, who are considered the founders of the Golden Age of Sciences. Natural medicines exist in various forms, including formulations such as tablets, powders, or extracts. Oils are among the oldest forms of medicinal herbal treatments and remain significant in the present time [9]. The use of herbs as a remedy depends on understanding their compositions that make them effective. Herbs contain compounds that interact with the human body in ways that promote healing and boost immunity. These substances, known as phytochemicals, are biologically active

substances that range from simple organic molecules to complex compounds [10]. Herbal remedies are used to treat minor health problems, such as nausea, constipation, headaches, digestive disorders, skin problems, and hair problems. Some medicinal herbs have been successful in treating certain chronic diseases, including respiratory problems, stomach ulcers, colitis, and arthritis [11].

Despite the widespread use of herbal oils in traditional and alternative medicine, there is a lack of data on natural radioactivity in herbal oils. The objective of this study is to measure natural radioactivity levels in selected herbal oil samples, assess radiation hazard parameters, estimate cancer risk probability, and evaluate potential genetic effects using low-energy gamma-ray spectroscopy.

This research is important to ensure the radiological safety of widely used herbal remedies and to support public health by providing data necessary for risk assessment and regulatory guidelines.

2 MATERIAL AND METHOD

2.1 Sample Collection and Preparation

In this paper, thirteen medicinal herbal oil samples, each with a volume of 50 ml, were collected from local markets, as shown in the Table 1. The samples were stored in 50 ml plastic containers for processing and measurement. The containers were sealed, and thick tape was wrapped around the lids to ensure airtight closure. The samples were stored for four weeks prior to measurement to allow for secular equilibrium between parent and daughter radionuclides.

Sample S12 is a commercial herbal oil labeled for female fertility, produced by Emad Company. The exact composition is not fully disclosed on the packaging, and it is marketed as a general-purpose women's care oil.

2.2 Radiation Detection System

It is crucial to evaluate the health risk of radiation for human's safety. The high-purity germanium detector was chosen for radionuclide analysis due to its excellent detection capability, allowing sufficient radionuclide quantities to be measured and radioisotope identification to be accurately determined. High-purity germanium detectors are a type of semiconductor detector used to detect gamma radiation. They are the ideal choice for analyzing gamma spectra and are more efficient than silicon detectors. The main characteristics of HPGe detectors are their high atomic number, high purity, high conductivity, low average energy required for electron-hole pair formation, and small size. It is crucial to evaluate the health risk of radiation for human's safety. The high-purity germanium detector was chosen for radionuclide analysis due to its excellent detection capability, allowing sufficient radionuclide quantities to be measured and radioisotope identification to be accurately determined [12], [13].

A low-energy high-purity germanium (HPGe) detector (Model BE5030P), designed for enhanced sensitivity at low gamma-ray energies, was employed in this study. It features a 5000 mm² active area, 31.5 mm crystal thickness, and a 0.6 mm carbon epoxy window. The detector was cooled with liquid nitrogen at -196 °C to reduce thermal noise, with samples positioned approximately 5.5 mm from the detector face. Energy calibration was performed using standard gamma-ray sources to ensure accurate channel-to-energy conversion in the low-energy range. Efficiency calibration was conducted with certified reference sources of similar geometry. The detector resolution (FWHM) was approximately 450 eV at 5.9 keV, 720 eV at 122 keV, and 1800 eV at 1332 keV. Background spectra were measured under identical conditions and durations (1–2 hours) and subtracted from sample spectra. Measurements were with counting times ranging from one to two hours per sample, optimized for low-energy gamma-ray detection.

2.3 Calculations

2.3.1 Specific Radioactivity

Specific radioactivity is the number of radioactive decays per unit time per unit mass or concentration.

$$A = \frac{C}{\varepsilon . I_g . m . t}, \quad (1)$$

where A is the radionuclide activity concentration (Bq/kg), C is the counting rate, ε is the detector efficiency for a given gamma ray energy, Ig is the absolute transmission gamma decay probability, m is the sample mass (kg) and t is the counting time (s) [14].

Table 1: Type and code of the samples.

No.	Code	Common name	Scientific name
1	S1	Paprika	Capsicum annuum
2	S2	Fenugreek	Trigonella foenum-graecum
3	S3	Castor	Ricinus communis
4	S4	Marjoram	Origanum majorana
5	S5	Cloves	Syzygium aromaticum
6	S6	Oliban	Boswellia sacra
7	S7	Cresson	Lepidium sativum
8	S8	Avocado	Persea americana
9	S9	Onion	Allium cepa
10	S10	Sesame	Sesamum indicum
11	S11	Garlic	Allium sativum
12	S12	Fertilization for women	---
13	S13	Chamomile	Matricaria chamomilla

2.3.2 Chemical Concentration

The elemental concentrations were determined using the relationships shown in Table 2.

Table 2: Conversion of specific activity to chemical concentration [15].

Specific activity (Bq/kg)	Chemical concentrations
12.35 $^{238}_{92}U$	1 U ppm
4.06 $^{232}_{90}Th$	1 Th ppm
313 $^{40}_{19}K$	1 K %

2.3.3 Radium Equivalent

Due to the heterogeneous distribution of radioactive nuclides in oil samples, exposure estimates were standardized by calculating the radium equivalent activity. This allows for a comparison of specific activity as follows [16], [17]:

$$\mathrm{Ra_{eq}} = \mathrm{A_U} + 1.43\,\mathrm{A_{Th}} + 0.077\,\mathrm{A_k} \qquad (2)$$

Were $\mathrm{A_U}, \mathrm{A_{TH}}, \mathrm{A_K}$ are the specific activity of $^{238}_{92}$U, $^{232}_{90}$Th and $^{40}_{19}$K in (Bq/kg).

2.3.4 Absorbed Dose

Absorbed dose is defined as the amount of energy transferred from radiation to matter, i.e. the energy absorbed by an object, measured in (Gy) unit. Were calculated using the following equation[5]:

$$\mathrm{D} = 0.427\,\mathrm{A_U} + 0.662\,\mathrm{A_{Th}} + 0.043\,\mathrm{A_K} \qquad (3)$$

Were $\mathrm{A_U}, \mathrm{A_{TH}}, \mathrm{A_K}$ are the specific activity of $^{238}_{92}$U, $^{232}_{90}$Th and $^{40}_{19}$K in (Bq/kg).

2.3.5 External and Internal Hazard Index (Hex, Hin)

The determination of external hazard indices assists in estimating the expected gamma radiation dose, whereas internal hazard indices, which are more critical, contribute to assessing the dose received by an individual through the ingestion or inhalation of gamma emitters. Both indices were calculated using the given equations [18].

$$\mathrm{H_{in}} = \frac{\mathrm{A_U}}{185} + \frac{\mathrm{A_{Th}}}{259} + \frac{\mathrm{A_K}}{4810}, \qquad (4)$$

$$\mathrm{H_{ex}} = \frac{\mathrm{A_U}}{370} + \frac{\mathrm{A_{Th}}}{259} + \frac{\mathrm{A_K}}{4810}. \qquad (5)$$

Were $\mathrm{A_U}, \mathrm{A_{TH}}, \mathrm{A_K}$ are the specific activity of $^{238}_{92}$U, $^{232}_{90}$Th and $^{40}_{19}$K in (Bq/kg).

2.3.6 Annual Gonadal Equivalent Dose (AGED)

The Annual Gonadal Equivalent Dose (AGED) is a radiation measure used to estimate the equivalent radiation dose received by the gonads over a year. Due to the high sensitivity of reproductive organs to ionizing radiation, this measure is considered a key criterion in exposure assessment. Any damage to the genetic material (DNA) caused by radiation can potentially lead to genetic mutations, which may have long-term hereditary consequences [19], [20]. Were calculated as follows [21]:

$$\mathrm{AGDE\ (\mu Sv \cdot y\text{-}1)} = 3.09\,\mathrm{A_U} + 4.18\,\mathrm{A_{Th}} + 0.314\,\mathrm{A_K}. \qquad (6)$$

Were $\mathrm{A_U}, \mathrm{A_{TH}}, \mathrm{A_K}$ are the specific activity of $^{238}_{92}$U, $^{232}_{90}$Th and $^{40}_{19}$K in (Bq/kg).

2.3.7 The Annual Effective Dose (AED)

Based on the absorbed dose, the annual effective internal and external doses were calculated as follows[22]:

$$\text{In AED}\left(\frac{\mu Sv}{y}\right) = D \times 8766 \times 0.8 \times 0.7, \quad (7)$$

$$\text{Out AED}\left(\frac{\mu Sv}{y}\right) = D \times 8766 \times 0.2 \times 0.7. \quad (8)$$

Where 0.7 Sv/Gy is the dose conversion factor, 0.2 and 0.8 are the external and internal occupancy factors, respectively, 8766 is the time conversion factor.

2.3.8 Excess Lifetime Cancer Risk (ELCR)

Calculating the probability of cancer incidence helps determine the percentage of individuals who may develop cancer as a result of receiving the annual effective dose [15].

$$\text{In ELCR} = \text{AED (indoor)} \times DL \times RF, \quad (9)$$

$$\text{Out ELCR} = \text{AED (outdoor)} \times DL \times RF. \quad (10)$$

DL is the average human lifespan is about 70 years, with RF representing the risk factor for radiation-induced cancer per sievert, with a value of 0.05 f, according to the ICRP (International Commission on Radiological Protection).

3 RESULTS AND DISCUSSION

Table 3 presents the specific activity results for uranium, thorium, and potassium, with average values of 11.519 Bq/kg, 2.2 Bq/kg, and 77.77 Bq/kg, respectively. Based on the conversion factors in Table 2, the calculated concentrations of these elements were 0.933 ppm, 0.542 ppm, and 0.248%, respectively. Regarding uranium, the highest concentration was found in the garlic oil sample, while the lowest was in chamomile oil (S13). The highest potassium concentration was observed in garden cress oil (S7), whereas the lowest was in onion oil (S9). Thorium was not detected in 12 samples and was only present in the onion oil sample (S9). There are several possible reasons for the presence of thorium in the onion sample. One possibility is that the onion was cultivated in soil naturally rich in thorium. Additionally, as a root vegetable that grows directly within the soil, onions may have a higher capacity to absorb elements from the soil more efficiently compared to other plants. By comparing all radioactive activity values with the globally permissible limit, it is evident that all values are significantly lower than the global average. Therefore, they are considered radiologically safe.

Table 3: Activity and chemical concentration of uranium, thorium and potassium of oil samples.

Sample Code	Activity (Bq/kg)			Chemical concentration		
	^{238}U	^{232}Th	^{40}K	U (ppm)	Th (ppm)	K (%)
S1	12.4±1.4	BDL	100.96	1.004	BDL	0.323
S2	9.8±1.4	BDL	71.20± 2.4	0.794	BDL	0.227
S3	11.5±1.3	BDL	85.20±3.9	0.931	BDL	0.272
S4	13.8±0.6	BDL	137.68±6.3	1.117	BDL	0.440
S5	9.960.6	BDL	BDL	0.806	BDL	BDL
S6	12.4±1.6	BDL	81.50±3.9	1.004	BDL	0.260
S7	14.7±1.3	BDL	140.70±6.8	1.190	BDL	0.450
S8	14.6±1.2	BDL	113.20±6.54	1.182	BDL	0.362
S9	11.7±1.3	16.500± 0.23	2.96±0.07	0.947	4.064	0.009
S10	11.9±1.4	BDL	108.17	0.964	BDL	0.346
S11	15.6±1.4	BDL	78.70±3.4	1.263	BDL	0.251
S12	12.77±1.23	BDL	5.29±.12	1.034	BDL	0.017
S13	3.03±0.07	BDL	100.29±5.4	0.245	BDL	0.320
Average	11.519	2.200	77.770	0.933	0.542	0.248
Standard deviation	3.172	0.257	4.576	1.127	48.104	0.154
Global average [23]	35	30	400	2.83	7.38	1.28
B.D.L = Below Detection Limit. The maximum value. The minimum value.						

The radium equivalent activity (Raeq), absorbed dose rate (D), internal hazard index (Hin), and external hazard index (Hex) were calculated. As shown in Table 4, the average values for these parameters are 20.149 Bq/kg, 9.411 nGy/h, 0.085, and 0.054, respectively. These values are considerably lower than the global averages.

Figure 1 illustrates the relationship between uranium radioactivity and radium equivalent activity, where the red points represent the data and the blue line shows the linear regression. The regression equation y=1.1713x+5.8602y=1.1713x+5.8602 indicates that for each unit increase in uranium radioactivity, Raeq increases by approximately 1.1713 Bq/kg, with an intercept of 5.8602 Bq/kg. The regression coefficient R2=0.2933$R2$=0.2933 indicates a weak linear correlation, meaning that only about 29.33% of the variation in Raeq is explained by uranium radioactivity.

Figure 2 shows that sample S9 has the highest internal and external hazard indices, 0.128 and 0.096, respectively, while the lowest values were recorded for sample S13. This indicates a lower associated health risk for sample S13 compared with the others.

Table 4: Radiological hazard indices of the analyzed oil samples.

Sample Code	Ra_{eq} (Bq/kg)	D (nGy/h)	H(in)	H(ex)
S1	20.174	9.636	0.088	0.055
S2	15.282	7.246	0.068	0.041
S3	18.060	8.574	0.080	0.049
S4	24.401	11.813	0.103	0.066
S5	9.960	4.253	0.054	0.027
S6	18.676	8.799	0.084	0.050
S7	25.534	12.327	0.109	0.069
S8	23.316	11.102	0.102	0.063
S9	35.523	16.046	0.128	0.096
S10	20.229	9.733	0.087	0.055
S11	21.660	10.045	0.101	0.059
S12	13.177	5.680	0.070	0.036
S13	10.752	5.606	0.037	0.029
Average	20.149	9.411	0.085	0.054
Standard deviation	6.859	3.193	0.024	0.019
Global average[5], [23]	370	≤ 1	≤ 1	55
The maximum value.				
The minimum value.				

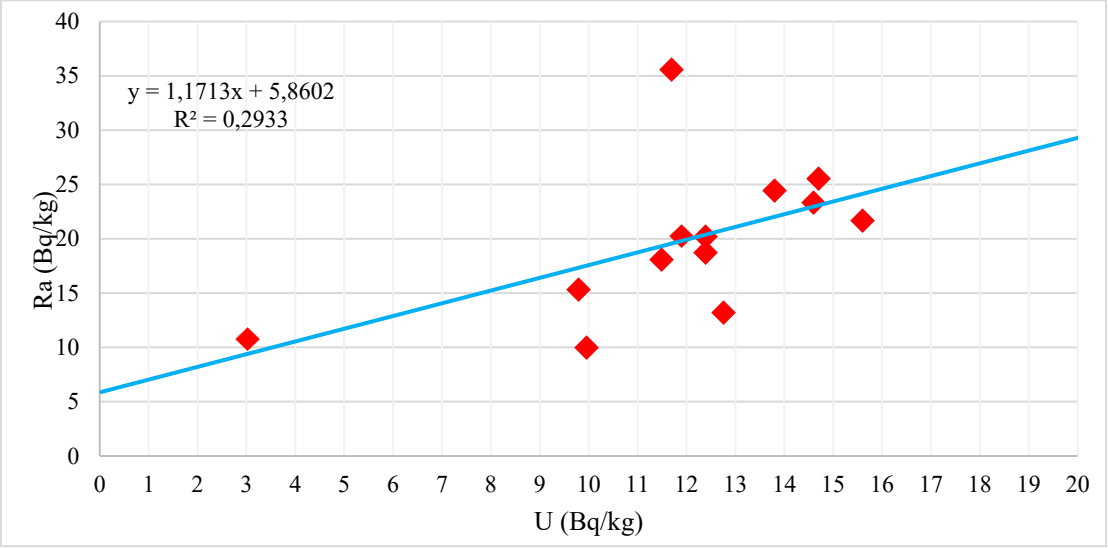


Figure 1: The correlation between uranium specific activity and radium specific activity in the oil samples. The red dots represent data points; the blue line shows the linear regression trend where $R^2 = 0.2933$.

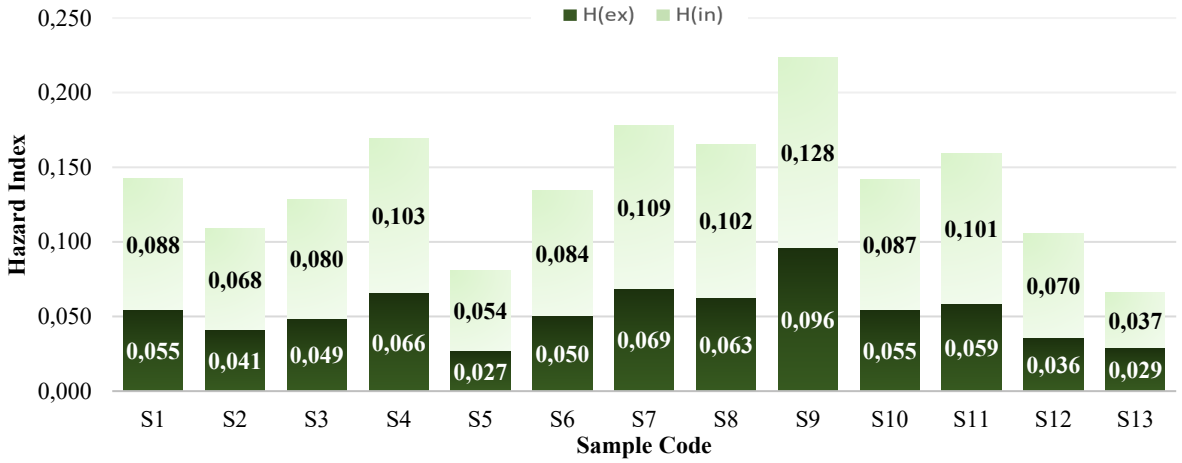


Figure 2: External (Hex) and Internal (Hin) hazard indexes for oil samples.

Table 5: AGDE, AEDE and ECLR (Indoor, outdoor and total).

Sample Code	AGDE	AED (μSv/y)			ELCR		
		Indoor	Outdoor	Total	Indoor	Outdoor	Total
S1	0.070	0.047	0.012	0.059	0.182	0.046	0.228
S2	0.053	0.036	0.009	0.044	0.137	0.034	0.171
S3	0.062	0.042	0.011	0.053	0.162	0.041	0.203
S4	0.086	0.058	0.014	0.072	0.223	0.056	0.279
S5	0.031	0.021	0.005	0.026	0.080	0.020	0.100
S6	0.064	0.043	0.011	0.054	0.166	0.042	0.208
S7	0.090	0.061	0.015	0.076	0.233	0.058	0.291
S8	0.081	0.054	0.014	0.068	0.210	0.052	0.262
S9	0.106	0.079	0.020	0.098	0.303	0.076	0.379
S10	0.071	0.048	0.012	0.060	0.184	0.046	0.230
S11	0.073	0.049	0.012	0.062	0.190	0.047	0.237
S12	0.041	0.028	0.007	0.035	0.107	0.027	0.134
S13	0.041	0.028	0.007	0.034	0.106	0.026	0.132
Average	0.067	0.046	0.012	0.058	0.178	0.044	0.222
Standard deviation	0.021	0.016	0.004	0.020	0.060	0.015	0.075
Global average [15], [24]	0.3	0.42	0.08	0.5	1.16	0.29	1.45
The maximum value.							
The minimum value.							

Table 5 presents the data for both gonadal radiation exposure and the annual effective dose, which is divided into internal, external, and total components. It also shows the cancer risk probability, likewise divided into internal, external, and total. The values follow the same trend, where the lowest values for all parameters are observed in sample S5, highlighted in green, indicating low radiation levels in this sample. Sample S9, highlighted in blue, has the highest values, suggesting a higher concentration of radionuclides. All values fall within the permissible limits set by the World Health Organization, indicating that the medicinal herbal oils in this study do not pose a risk to consumers.

Figure 3 is a line graph that shows the variation of different (AGED) values across each sample. The values range between 0.03 and 0.10, with noticeable fluctuations among the samples, indicating differences in the composition of the oils in terms of radionuclide concentrations.

Figure 4a is a bar chart divided into two parts: the light color represents the internal annual effective dose, while the dark color represents the external annual effective dose. All internal dose values are higher than the external ones. As shown in Figure 4b,

the difference is clear, with the internal dose accounting for 80% of the total dose, whereas the external dose represents only 20%. This indicates that most of the radiological risk comes from being in enclosed environments and internal exposure, while outdoor radiation exposure is less significant.

Figure 5 is a bar chart illustrating the values of cancer risk probability. Each bar is divided into two sections: the lighter portion represents internal risk, while the darker portion represents external risk. All internal values are significantly higher than the external ones, accounting for approximately 80% of the total values. This indicates that radiation risks from outdoor exposure are much lower compared to those from internal exposure and enclosed environments.

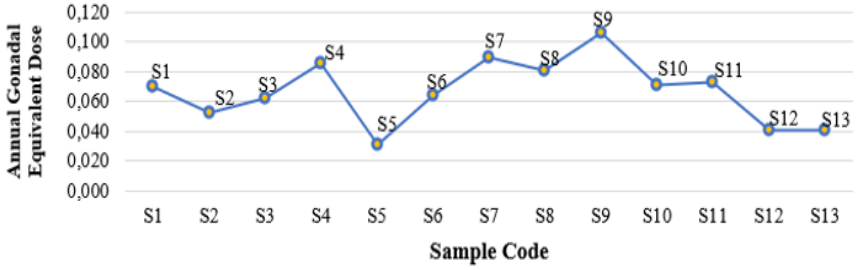


Figure 3: Annual gonadal equivalent dose (AGED) value for each oil sample.

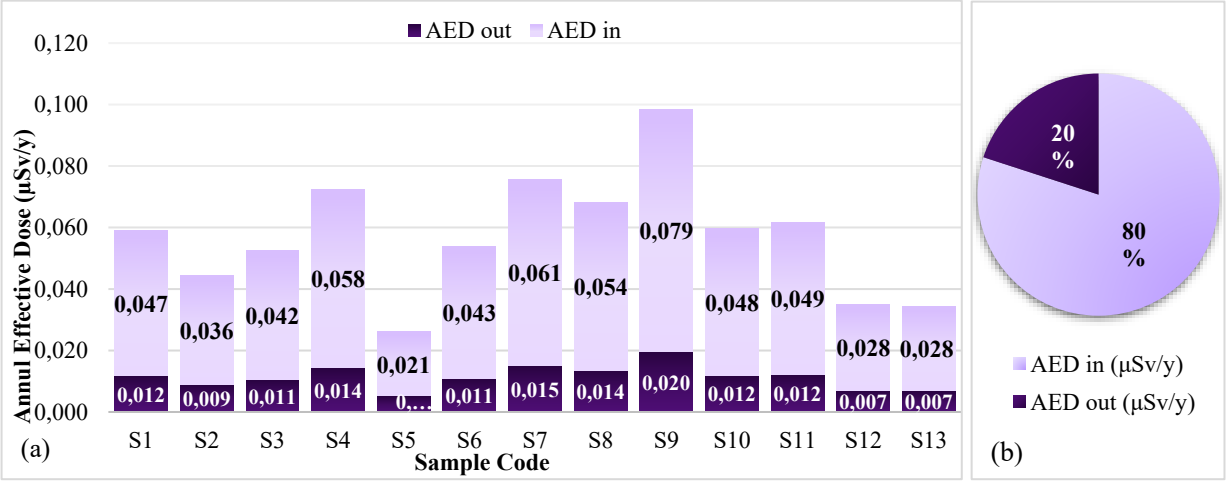


Figure 4: AED analysis for oil samples: a) AED (indoor, outdoor) for oil samples; b) proportional contribution of internal and external AED.

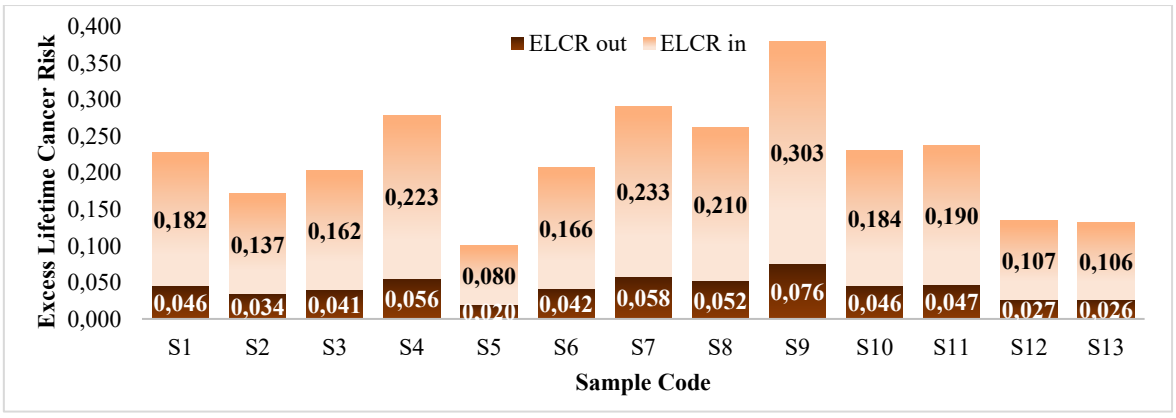


Figure 5: ELCR (indoor, outdoor) for oil samples.

4 CONCLUSIONS

The results confirm that all the medicinal herbal oils are radiologically safe for human consumption and therapeutic use. Sample S11 (garlic oil) showed the highest concentration of uranium, and sample S9 (onion oil) was the only sample containing detectable thorium. Therefore, continuous monitoring of oils derived from root-based plants is recommended. Soil quality should be monitored, and cultivation should be done in low-radiation soils to minimize the uptake of radionuclides. In summary, this study confirms that the analyzed herbal oils do not pose a significant radiological threat to consumers, supporting their continued use in traditional and alternative medicine.

In light of the increasing global use, a broader evaluation of herbal medicines and assessment of their radiological safety are essential. Future studies should therefore expand their scope to include a wider range of herbal oil types and investigate the effects of soil composition, agricultural practices, and the refining process on the transfer of radionuclides.

Overall, this research contributes to the radiological monitoring of herbal oils and provides data for international health authorities. It also reinforces the need for regular quality control to ensure that the products in use remain safe and beneficial for public health.

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Trace Element Risk Assessment in Medicinal Herbal Oils

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Keywords: Herbal Oil, Heavy Metal, ICP-OES, Estimated Daily Intake (EDI), Cancer Risk.

Abstract: This paper highlights the need for regular monitoring of heavy metal levels in herbal oils, as it assessed concentrations of trace metals (Cd, Cr, Pb, U, Zn) in nine herbal oil samples including olive, sesame, castor, peppermint and sidr oils, along with blends for joints, hair, colon health, and antibacterial use. Samples were analyzed using ICP-OES to determine metal levels. Health risk assessments were conducted through the computation of the Cancer Risk (CR), Hazard Quotient (HQ), Hazard Index (HI), and Estimated Daily Intake (EDI), based on recommended intake rates (Chinese Pharmacopoeia) and WHO body weight standards. Results showed uranium had the highest mean concentration (0.501 ppm), with other metals averaging below 0.03 ppm. All calculated EDI values were significantly below respective PTDI limits, suggesting low non-carcinogenic risk. HQ values for individual elements and cumulative HI remained well below the threshold of 1, indicating safe exposure levels. However, CR values for lead exceeded the widely accepted lifetime cancer risk benchmark of 1×10^{-6} set by the World Health Organization (WHO) in some samples, indicating a potential concern associated with long-term exposure. These findings highlight the need for routine monitoring and stricter regulation of heavy metal content, particularly uranium, in herbal oil preparations to ensure consumer safety and reduce potential long-term health risks.

1 INTRODUCTION

For thousands of years, medicinal plants have been widely used in traditional medicine, and recently they have been incorporated into many pharmaceutical, food, and cosmetic industries [1]. Despite their widespread use, there is increasing concern regarding the safety of these herbal products because of reports of elevated levels of heavy metals in certain herbal formulations. Although they contain various essential elements and trace elements that contribute to their therapeutic properties, they may pose health risks when present at elevated concentrations. This problem has been linked to various health complications, including acute kidney diseases [2]-[4]. Studies in both developed and developing countries have shown levels of toxic metals that have raised concerns in commercial herbal products. These metals can bioaccumulate in plants from contaminated soil and enter the food chain, thereby posing health risks to living organisms [5], [6], as the reduced renal clearance of many heavy metals exacerbates these risks through their accumulation in the body over time [7]. Plant uptake of metals is influenced by soil properties such as pH, redox potential, fertility, and organic matter content, and is distributed throughout all plant tissues depending on plant-specific characteristics [8], [9]. What underscores the need to measure uranium levels alongside other toxic elements in herbal products is that naturally occurring radioactive elements such as uranium are part of the soil and rock composition. Owing to its wide occurrence in natural soils and geological formations, it can contribute to environmental contamination. These elements, along with their decay products, such as radium and radon, can enter the soil–plant system and may be absorbed by medicinal plants. Thus, they represent an additional source of contamination [10]. In addition, contamination often results from environmental pollution, including industrial emissions, vehicle exhaust, and the use of agricultural chemicals [11]. In herbal oils, the presence of trace metals may accelerate oxidative degradation processes, producing free radicals and potentially carcinogenic by products [12].

This study focused on medicinal herbal oils available on the Iraqi market, including locally produced blended formulations and commonly used oils. Although there have been studies addressing heavy metals in herbal products, information on their

levels in oil-based preparations remains limited. In addition to determining element concentrations, evaluating the potential long-term health risks associated with exposure to trace metals is important. In general, herbal oils are often used repeatedly over long periods; even minimal amounts of metal may accumulate in the body over time, raising safety concerns.

The aim of this study was to determine the concentrations of selected heavy metals (cadmium, chromium, lead, uranium, and zinc) in four medicinal herbal blends used for joint treatment, hair problems, antibacterial and antifungal purposes, and colon health, in addition to olive oil, sesame oil, castor oil, peppermint oil, and sidr oil by calculating element levels and assessing the potential hazards to one's health from their use.

2 MATERIALS AND METHODS

2.1 Sample Collection

The therapeutic oils were purchased from local popular markets; four of them were herbal oil blends. The first blend, which is used for treating joint and muscle pain, consists mainly of clove, mint, and harmala oils as the primary components, in addition to small amounts of other carrier oils. The second blend was intended for hair problems and contained mainly castor, olive, and violet oils, with a small amount of rosemary oil and other oils. The third blend, designed to treat colonic issues, was composed of clove, mint, orange, and pumpkin oils as the main ingredients. The fourth and final blend, an antibacterial and antifungal mixture, included clove, cinnamon, bay leaf, and castor oils, along with small amounts of light carrier oils. In addition, four commonly used oils were purchased: olive, sesame, castor, mint and sidr. All the samples were stored in tightly sealed plastic containers in a suitable dry environment until analysis was performed.

2.2 Sample Preparation Method

The nine samples were prepared via wet thermal digestion to convert the mineral components into a form suitable for ICP–OES analysis. A one-gram portion of each sample was taken and placed in a glass beaker with 10 ml of sulfuric acid. The mixture was then heated on a hot plate until complete digestion in acid. After cooling, the sample was filtered through filter paper, and the filtrate was transferred to a digestion vessel. Then, 10 ml of nitric acid and 5 ml of hydrogen peroxide were added. The container was sealed tightly and placed in a microwave under high pressure, gradually increasing from 10 to 100 bar, and at a temperature ranging from 25°C to 200°C for 15 minutes, followed by holding at 200°C for another 15 minutes, resulting in a total digestion time of 30 minutes. The sample was then gently cooled, transferred to a glass beaker, and evaporated on a conventional heater to remove excess acid. Afterward, the sample was cooled again and filtered into a volumetric flask, and high-purity water was added to reach a final volume of 50 ml. The prepared solutions were stored until analysis.

2.3 ICP-OES Instrumentation and Analysis

An Agilent 5800 ICP–OES instrument, was used in this study to determine the composition of the samples. Inductively coupled plasma–optical emission spectrometry is widely used for many elements because of its high accuracy and sensitivity in detecting a wide range of elements, even at low levels. The instrument works by nebulizing the sample through a spray system to introduce it into plasma generated by inductive electromagnetic coupling at a power of 1.2 kW. The sample is ionized inside the plasma at a temperature exceeding 6000 K, causing the elements in the sample to emit characteristic optical spectra. After these emission lines are detected, they are analyzed via spectrometers and detectors integrated into the system.

Table 1: Type and code of the samples.

No.	Sampel name	Code
1.	Oliv oil	Yt1
2.	Sesame oil	Yt2
3.	Castor oil	Yt3
4.	Peppermint oil	Yt4
5.	Joint Oil Blend	Yt5
6.	Hair Nourishing Oil Blend	Yt6
7.	Herbal Oil Blend for Colon	Yt7
8.	Antibacterial Oil Blend	Yt8
9.	Sidr oil	Yt9

2.4 Health Risk Assessment of Heavy Metals in Herbal Oils

The health risk of the ingestion of heavy metal-contaminated herbal oils was evaluated via exposure assessment (EDI), noncarcinogenic risk assessment (HQ, HI) and carcinogenic risk assessment (CR). These methods provide tools for assessing the

possible health consequences of heavy metal exposure in relation to herbal oils [13]. Acceptable daily consumption (TDI) "An estimate (with uncertainty spanning perhaps an order of magnitude) of a daily oral exposure to the human population (including sensitive subgroups) that is likely to be without appreciable risk of deleterious effects during a lifetime" is the definition of the reference dose (RfD) for hazard dose, which was introduced by the U.S. Environmental Protection Agency (EPA). Importantly, that the use of RfD eliminates the implication that any exposure level is entirely safe or acceptable [14].

2.4.1 Exposure Assessment

The estimated daily intake (EDI, mg·kg^{-1}·day^{-1}·bw) of each metal in the analyzed samples was calculated to evaluate potential health risks [15]. In these calculations, C (mg·kg^{-1}) represents the concentration of the metal in the oil. IRD (kg·day^{-1}) is the daily intake rate, which is set at 0.02 kg/day. Ef (days·year^{-1}) denotes the frequency of exposure, which is thought to be 350 days annually. The exposure length is indicated by Ed (years), which is set at 30 years. BW (kg) represents body weight, which is assumed to be 70 kg [5]. The estimated daily intake (EDI) is calculated according to the following formula:

$$\mathrm{EDI} = \frac{\mathrm{C} \times \mathrm{IRD} \times \mathrm{Ef} \times \mathrm{Ed}}{\mathrm{BW}} \quad (1)$$

2.5 Noncarcinogenic Risk Assessment

Noncarcinogenic health risks associated with heavy metal exposure through herbal oils were evaluated via the hazard quotient (HQ) and hazard index (HI). The HQ for each metal was calculated by comparing the estimated daily exposure with the oral reference dose (RfD) according to the following equation [16]:

$$\mathrm{HQ} = \frac{\mathrm{EDI}}{\mathrm{AT} \times \mathrm{RfD}} \quad (2)$$

where EDI is the estimated daily intake and AT is the averaging time for noncarcinogenic effects, which is calculated as days. RfD values (mg·kg^{-1}·day^{-1}) were adopted as follows: Cd=0.001, Cr=1.5, Pb=0.004, and Zn=0.3[17], [18].

The HQ values for each metal were calculated for all the samples. The sum of individual HQs provided the hazard index (HI) for each sample:

$$\mathrm{HI} = \Sigma \mathrm{HQ} \quad (3)$$

An HQ or HI below 1 indicates no significant noncarcinogenic risk for the exposed population, whereas values equal to or exceeding 1 suggest potential health concerns based on the World Health Organization (WHO).

2.6 Carcinogenic Risk Assessment

The carcinogenic risk (CR) was estimated for selected heavy metals in the herbal oils via the following equation [16]:

$$\mathrm{CR} = \frac{\mathrm{EDI} \times \mathrm{SFo}}{\mathrm{AT}} \quad (4)$$

where EDI is the estimated daily intake, AT is the averaging time for carcinogenic effects, calculated as 70 years × 350 days/year, and SFo is the oral slope factor (mg^{-1}·kg·day) indicating cancer potency. The oral slope factor (SFo) values adopted for this assessment were: Cd=100, Cr=10, Pb=100, and Zn=3 on the basis of data provided by the ATSDR (Agency for Toxic Substances and Disease Registry).

3 RESULTS AND DISCUSSION

Table 1 presents the types and codes of the analyzed herbal oil samples. Each sample was assigned a specific code (Yt1–Yt8) for identification and reference throughout the study.

The concentrations of Cd, Cr, Pb, U, and Zn in the analyzed herbal oil samples are shown in Table 2 below, and are expressed in ppm. Table 3 presents the estimated daily intake (EDI) values for these elements in mg·kg^{-1}·day^{-1}·bw, scaled by 10^{-6}, together with the corresponding provisional tolerable daily intake (PTDI) limits.

Table 2: Elemental concentrations in herbal oil samples.

Code	Element Concentration (ppm)				
	Cd	Cr	Pb	U	Zn
Yt1	LOD	0.02	0.01	0.29	0.01
Yt2	0.01	0.03	0.07	0.48	0.01
Yt3	LOD	0.01	0.01	0.44	0.01
Yt4	LOD	0.01	0.01	0.40	LOD
Yt5	LOD	0.02	0.02	0.48	LOD
Yt6	0.01	0.02	0.05	0.59	LOD
Yt7	LOD	0.01	0.03	0.68	0.01
Yt8	LOD	0.02	0.02	0.65	LOD
Yt9	LOD	0.02	0.01	0.57	LOD
Max	0.01	0.03	0.07	0.68	0.01
Min	LOD	0.01	0.01	0.29	LOD

LOD: Limit of detection.

Table 3: Estimated Daily Intake (EDI) values for metals ($mg \cdot kg^{-1} \cdot day^{-1} \cdot bw \times 10^{-6}$) compared with PTDI.

Code	EDI ($mg\ kg^{-1}\ day^{-1} \cdot bw$) $\times 10^{-6}$				
	Cd	Cr	Pb	U	Zn
Yt1	LOD	5.71	2.86	82.9	2.86
Yt2	2.86	8.57	20	137	2.86
Yt3	LOD	2.86	2.86	126	2.86
Yt4	LOD	2.86	2.86	114	LOD
Yt5	LOD	5.71	5.71	137	LOD
Yt6	2.86	5.71	14.3	169	LOD
Yt7	LOD	2.86	8.57	194	2.86
Yt8	LOD	5.71	5.71	186	LOD
Yt9	LOD	5.71	2.86	163	LOD
Max	2.86	8.57	20	194	2.86
Min	LOD	2.86	2.86	82.9	LOD
PTDI	1×10-3	0.003	0.005	0.0006	0.3

ND = not detected. For calculation purposes, values below the detection limit (LOD) were replaced by the LOD value.

Table 2 shows that uranium had the highest mean concentration (0.501 ppm), which was significantly greater than that of the other elements, where the concentrations of the remaining elements did not exceed 0.03 ppm. This clear variation can be explained by the geochemical behavior of uranium and its tendency to accumulate in plant-derived materials. In contrast, cadmium, chromium, and zinc showed very slight variation among the samples (≤ 0.01 ppm), indicating relative stability in their background levels. On the other hand, lead showed greater fluctuations in concentration (0.01–0.07 ppm), which may be attributed to differences in environmental pollution sources, processing conditions, or even storage factors. This variation in lead levels highlights the possibility of heterogeneous distribution in herbal oils, making monitoring of lead more important than monitoring to other elements with more stable behavior.

In Table 3, all the calculated EDI values were several orders of magnitude lower than their corresponding PTDI limits. For example, the maximum EDI for uranium was 194×10^{-6} $mg \cdot kg^{-1} \cdot day^{-1}$, whereas its PTDI was 0.0006 $mg \cdot kg^{-1} \cdot day^{-1}$ (600×10^{-6}), indicating that consumption remains below the tolerable limit. Lead (Pb) had a maximum EDI of 20×10^{-6} whereas its PTDI was 0.005 $mg \cdot kg^{-1} \cdot day^{-1}$ (5000×10^{-6}). For cadmium (Cd), chromium (Cr), and zinc (Zn), the highest EDIs ($2.86\text{-}8.57\times10^{-6}$) were also far below their respective PTDI values.

These results suggest that, on the basis of the estimated daily intake, the consumption of the tested herbal oils does not pose a significant noncarcinogenic health risk with respect to the assessed metals. However, the relatively high uranium concentrations warrant attention, given their bioaccumulative nature and potential for local variations in exposure.

The calculated HQ, HI, and CR values for Cd, Cr, Pb, and Zn in the analyzed herbal oil samples are presented in Table 4 below.

In Table 4, all HQ values for the studied elements in the samples clearly decreased (HQ < 1). These findings indicate that the daily consumption of these oils does not cause noncarcinogenic toxic effects. It was also found that lead is the most influential element due to its relatively greater contribution in most samples than the other elements, in addition to its higher toxicological relevance, which results in a lower reference value. Nevertheless, all HQ values for lead remained below the health concern threshold, indicating that the exposure level is still within the safe range. Moreover, the other elements contributed very low values, reflecting their weak impact.

Table 4: HQ, HI, and CR values for metals in herbal oils.

Code	HQ ($\times10^{-3}$)				HI ($\times10^{-3}$)	CR ($\times10^{-4}$)			
	Cd	Cr	Pb	Zn		Cd	Cr	Pb	Zn
Yt1	LOD	0.004	0.714	0.010	0.001	LOD	0.234	0.117	0.004
Yt2	2.857	0.006	5	0.010	0.008	0.117	0.352	0.822	0.004
Yt3	LOD	0.002	0.714	0.010	0.001	LOD	0.117	0.117	0.004
Yt4	LOD	0.002	0.714	LOD	0.001	LOD	0.234	0.117	LOD
Yt5	2.857	0.004	1.429	LOD	0.001	0.117	0.234	0.235	LOD
Yt6	LOD	0.004	3.571	0.010	0.006	LOD	11.74	0.587	0.004
Yt7	LOD	0.002	2.143	LOD	0.002	LOD	0.234	0.352	LOD
Yt8	LOD	0.004	1.429	LOD	0.001	LOD	0.234	0.235	LOD
Yt9	LOD	0.004	0.714	LOD	0.001	LOD	0.117	0.117	LOD
Max	2.857	0.006	5	0.010	0.008	0.117	0.352	0.822	0.004
Min	LOD	0.002	0.714	LOD	0.001	LOD	0.117	0.117	LOD
WHO limit	1				1	1×10^{-6}–1×10^{-4}			

ND = Not Detected. For calculation purposes, values below the detection limit (LOD) were replaced by the LOD value.

The hazard index (HI) denotes the cumulative impact of the analyzed elements (Cd, Cr, Pb, and Zn), with all computed values for the examined samples significantly less than one (HI < 1). The HI values ranged from 0.001 $\times 10^{-3}$ to 0.008 $\times 10^{-3}$, demonstrating that the cumulative noncarcinogenic risk associated with the ingestion of these herbal oils is minimal and remains within globally established safety limits. These data demonstrate that the regular use of these oils is unlikely to induce adverse noncarcinogenic health effects. Variations detected in HI values among the samples are related mainly to changes in lead (Pb) concentrations, which had higher HQ contributions than did cadmium, chromium, and zinc, whereas the latter had very little effect on the total HI. This trend highlights the importance of monitoring lead levels to reduce cumulative noncarcinogenic health hazards.

In terms of carcinogenic risk (CR), lead had CR values between 0.117 $\times 10^{-4}$ and 0.822 $\times 10^{-4}$, indicating that some samples were close to the upper limit of the acceptable carcinogenic risk range (1×10^{-6}–1×10^{-4}) [19], In contrast, cadmium, chromium, and zinc consistently presented much lower CR values, remaining well within safe limits. This observation suggests that lead is the main contributor to the estimated carcinogenic risk among the analyzed elements. Although the calculated CR values do not exceed the recommended limits, the possibility of long-term exposure through repeated consumption should be carefully considered. Accordingly, greater attention should be given to controlling lead concentrations in herbal oils, alongside the implementation of stricter quality assurance measures and further studies focusing on the bioavailability and chemical behavior of lead. Such efforts would provide a more realistic evaluation of potential health risks associated with prolonged use.

Figure 1 shows the HQ values for Cd, Cr, Pb, and Zn in all the oil samples. Uranium has the highest HQ values across all samples, standing out clearly in the graph. The other elements have much lower HQ values, with small differences between samples. This visual comparison reveals that all HQ values remain well below the reference limit of 1, suggesting that there is no significant noncarcinogenic risk from these metals in the oils.

Figure 2 shows the CR values for the same elements in the samples. Lead again displays the highest CR values relative to the other elements, particularly in samples Yt2, Yt6, and Yt7, whereas cadmium, chromium, and zinc maintain continuously low cancer risk values. The figure also indicates modest changes in CR values among the samples, reflecting differences in element concentrations. Overall, the results indicate that the carcinogenic risk posed by Cd, Cr, and Zn is insignificant, but lead constitutes the dominant contributor to the projected cancer risk, although remains within the permissible reference range.

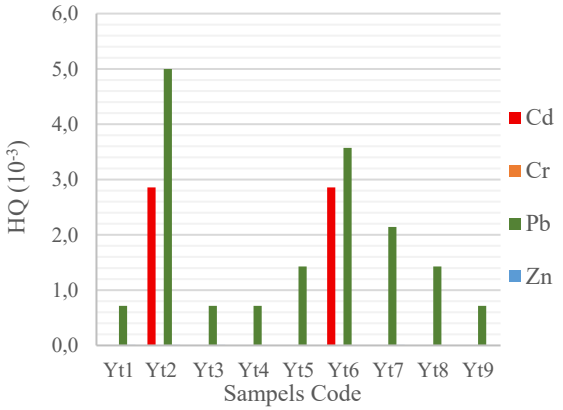


Figure 1: HQ Values of heavy metals (Cd, Cr, Pb, Zn) in nine herbal oil samples.

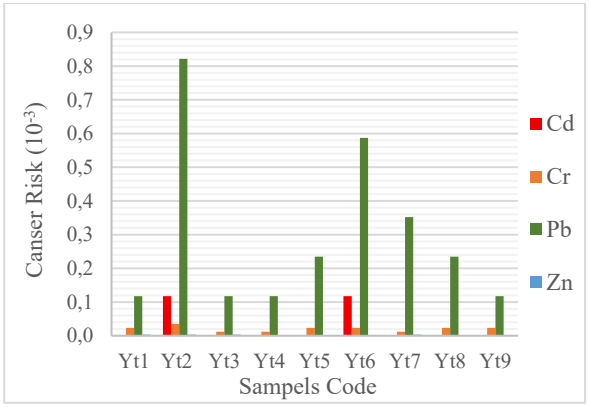


Figure 2: Cancer Risk (CR) of heavy metals (Cd, Cr, Pb, Zn) in nine herbal oil samples.

Although uranium demonstrated the greatest quantity among the investigated elements, its potential health impact cannot be properly estimated via chemical carcinogenic risk models. The health issue linked with uranium exposure is principally radiological and related to internal alpha radiation following ingestion. Consequently, no chemical carcinogenic risk value was provided to uranium in this investigation. The detected uranium levels imply the necessity for future investigations focused on activity concentration measurements and radiological dose assessment to accurately determine the long-term health repercussions of uranium.

4 CONCLUSIONS

The results of this study revealed that the investigated herbal oils contained varying concentrations of the heavy metals Cd, Cr, Pb, and Zn. The concentrations of cadmium, chromium, lead, and zinc generally remained at relatively low levels across all the samples. The estimated daily intake (EDI) calculations indicated that all values were significantly lower than the permissible limits on the basis of the provisional tolerable daily intake (PTDI). In addition, the hazard quotient (HQ) and hazard index (HI) values were below the reference limit of unity, confirming the absence of significant noncarcinogenic health risks associated with the regular consumption of these oils.

In contrast, the carcinogenic risk (CR) assessment revealed that lead exceeded the acceptable reference level in some samples, indicating the possibility of long-term carcinogenic risks associated with chronic exposure. These findings demonstrate that the absence of noncarcinogenic risk does not necessarily eliminate the potential for long-term health concerns arising from prolonged exposure to toxic elements.

This study emphasizes the necessity of regular monitoring of heavy metal concentrations in herbal oils, with particular attention given to lead. Furthermore, future studies should focus on evaluating the bioavailability and chemical speciation of these elements to provide a more accurate assessment of their potential health impacts. Increasing consumer awareness regarding the safety of herbal products is also essential to ensure their safe use in both food and medicinal applications.

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Model-Based Optimization of the Operating Window for Electrophysical Silver Deposition Using a Dimensionless Regime Map

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Abstract: We present a quantitative characterization of the kinetics of silver deposition during electrophysical ionization (EPI), focusing on the roles of electric field strength E and interelectrode gap d. Series Δm(E) were obtained for d=1.5, 2, 3 cm. For small gaps, the yield exhibits a smooth, sigmoid-like increase followed by saturation (a plateau); at d=3 cm the curve becomes nonmonotonic - a pronounced maximum is followed by a decline - indicating a switch in the dominant mass-transfer step. The interpretation is developed within a steady-state formulation of the Nernst–Planck equations with a Robin (mixed) boundary condition at the cathode and a phenomenological "active-surface availability" factor η(E). It is shown that a decreasing η(E) adequately describes monotonic regimes, whereas for large d realistic reproduction of the peak and subsequent drop is achieved by introducing a peaked η(E) or a weak field dependence of the external mass-transfer coefficient $k_c(E)$. This behavioral shift is consistent with morphological evolution of the deposit - from a compact structure to a dendritic–porous one with a self-screening effect. The dimensionless drift parameter β=zFEd/RT and the Damköhler number Da=kcd/D define a regime map that orders the series by d and delineates the "operating window" for E. Practically, this implies maintaining the field near its optimum, providing gentle hydrodynamic mixing and thermal stabilization (particularly at d≥3 cm), and structurally suppressing field focusing. The results provide a basis for scaling EPI and for adaptive control of silver deposition.

1 INTRODUCTION

In many modern chemico-technological schemes one tries, almost inevitably, to solve two problems at once: to recover valuable metals and, at the same time, to clean the aqueous medium without relying on a constant stream of added reagents. This double task is now seen as a characteristic feature of "green" production routes rather than an optional improvement. Against this background, electrophysical ionization (EPI) stands out as a comparatively simple but promising option. In a usual EPI setup the operator really has only a few knobs to turn: mainly the electric field strength E and the interelectrode gap d; the liquid phase can remain chemically simple, and the hardware itself is compact and not overloaded with auxiliaries [1] - [4]. Such minimalism is attractive in practice, but it also means that we must understand much better how a particular pair (E, d) actually translates into a certain deposition rate and a measurable mass gain Δm. Without this understanding it is difficult to design robust processes or to think seriously about closed-loop control [4] - [6].

Silver is a convenient system on which to explore these questions. It is technologically important, its deposits are very sensitive to transport and kinetic conditions, and, from an experimental point of view, the mass gain can be followed by straightforward gravimetric measurements. When one performs series of experiments in flat-plate EPI cells, an interesting

pattern appears. The dependence of the deposited mass Δm on E at fixed d is not a simple straight rise. For small gaps $\Delta m(E)$ typically increases in a somewhat S-shaped fashion and then levels off, whereas for larger gaps the curve often shows a pronounced maximum and then begins to decline [5]. In other words, as the gap grows, the system "switches" from a monotonic saturation-type behavior to a bell-shaped one. This qualitative change suggests that the rate-limiting steps are no longer the same: electromigration, diffusion and surface morphology (roughness, porosity, partial passivation) start to interact in a different way. Under such conditions it is no longer true that simply increasing E yields more silver; beyond a certain point the effectively active surface shrinks, screening becomes important, and the marginal gain per unit field can even turn negative [5].

If we want to move from such qualitative statements to predictive tools, a purely heuristic discussion is not enough. A framework is needed in which ion transport and interfacial reaction are treated together, while morphology-related effects are taken into account in a form that is still manageable. From this point of view, steady-state one-dimensional formulations of the Nernst–Planck type are a natural starting point. Earlier studies have used such models, alongside mass-transfer-coefficient approaches, to analyze reactive transport under externally imposed electric fields and to compare alternative descriptions of ion exchange and deposition [7], [8]. However, these works are usually tied to specific reactor geometries or particular sorbent systems. They do not offer a compact, experimentally checked "regime map" that would organize the operating space of EPI directly in terms of E and d and provide simple, visual rules for selecting a suitable window of conditions [6] - [8].

A reasonable way to compress the complexity of the problem is to resort to nondimensional analysis. When the Nernst–Planck equation is combined with a mixed (kinetically limited) boundary condition at the cathode, two dimensionless groups appear in a very natural manner. One can identify a drift parameter β, which compares electromigration with diffusion, and a Damköhler number Da, which measures the competition between interfacial reaction and mass transport. Taken together, β and Da span a "regime plane" on which different qualitative behaviors of $\Delta m(E)$-from monotonic saturation to bell-shaped curves-can be located. If experimental data for EPI-driven silver deposition can be reliably mapped onto this (β, Da) plane, measurements obtained at different gaps should, at least to a large extent, collapse, and the transfer of operating conditions between geometries becomes more transparent [7], [9].

Of course, a continuum-level description on its own would be incomplete. Real electrodes are not smooth mathematical surfaces. Dendritic structures, porous layers and locally passivated patches strongly modify the effective active area and, therefore, the overall reaction rate. For this reason it is reasonable to introduce an "active-surface fraction" $\eta(E)$, which summarizes, in a compact form, how morphological evolution and field redistribution reduce the proportion of surface sites that participate in efficient deposition as E increases. Earlier work on electrochemically assisted ion-exchange and hybrid separation processes has shown that such reduced descriptions can remain both physically interpretable and practically useful, provided that they are linked back to experimental observations [1] - [3], [7], [8]. In the present study $\eta(E)$ plays precisely this bridging role: it connects a mathematically simple transport model with the kinetics that are actually observed on a morphology-evolving surface.

Verification at the microstructural level is, in this setting, not merely an illustration but a necessary part of the analysis. Micrographs of the deposited silver layers, obtained for different combinations of E and d, make it possible to relate specific regions of the (β, Da) plane to visible changes in morphology: the transition from relatively compact layers to porous or dendritic forms, the onset of screening and shadowing, and the appearance of unstable growth modes. Read against the background of existing knowledge on ion transport in external fields, ion-exchange systems and hybrid electrophysical methods [1] -[3], these observations help refine the choice of the phenomenological function $\eta(E)$ and delineate those operating windows in which the process remains both efficient and reasonably controllable.

Within this context, the main goal of the present work is to build a physically consistent and experimentally grounded description of the mass gain Δm during electrophysical silver deposition as a function of the electric field strength E and the interelectrode gap d, and to express the results in universal dimensionless coordinates (β, Da) [7]. On the modeling side we use a steady-state Nernst–Planck formulation with mixed boundary conditions at the cathode and include morphology-related effects through a phenomenological active-surface fraction $\eta(E)$. On the experimental side we employ a simple plane-parallel silver–water system with three gaps (d = 1.5, 2 and 3 cm) to obtain a family of $\Delta m(E)$

curves and accompanying microstructural characterizations.

The study is guided by two working hypotheses. First, a decreasing sigmoidal approximation for η(*E*) with only two adjustable parameters is sufficient to describe both the monotonic (sigmoidal) and the non-monotonic (bell-shaped) dependence of Δ*m* on *E* observed at different gaps, without introducing an excessive number of fitting constants and while keeping the parameters physically meaningful [7], [8]. Second, mapping the experimental data onto the (β, Da) plane should lead to a noticeable collapse of the curves obtained at different *d*, reveal a reasonably well-defined "optimal window" in β, and suggest clear rules for tuning the EPI regime and transferring operating conditions between geometries [7], [9].

These hypotheses can be reformulated in terms of more concrete tasks. In what follows we aim (i) to formulate and analyze the steady Nernst–Planck boundary-value problem for electrophysical silver deposition with an explicit active-surface fraction η(*E*); (ii) to select and justify a minimal yet flexible parametric form of η(*E*) that remains compatible with the observed microstructures; (iii) to introduce and interpret the relevant dimensionless groups β and Da and to construct a regime map for the experimental data; and (iv) to use this map to identify practically meaningful operating windows and to outline possible ways of mitigating morphological limitations through hydrodynamic and geometric modifications of the EPI setup [1]-[3], [6], [7].

2 MATERIALS AND METHODS

Experiments were performed in a flat, plane-parallel electrochemical cell in which silver plates (cathode/anode) served as electrodes and were fully immersed in distilled water. The interelectrode gap d was fixed at three values; parameter estimation was carried out jointly across all series (global fit). The active area A was defined by the aperture of the cell window.

A constant voltage V was applied to the electrodes, establishing a quasi-uniform electric field E=V/d. Each run was conducted for a prescribed dwell time τ; upon completion the cathode was rinsed, dried to constant mass, and the mass gain Δm was recorded on an analytical balance. The solution temperature was maintained at 25 ± 0.5 °C. Potential ohmic heating was monitored by repeating measurements at identical (E,d); the absence of systematic drift in Δm was taken as a sufficient criterion of thermal stability.

To enable comparison across series, mass was converted to a flux and to an equivalent current density by normalizing to A and τ and applying Faraday's law:

$$j = \frac{\Delta m}{M_{Ag} A \tau}, \quad i = zFj = \frac{zF\Delta m}{M_{Ag} A \tau} \qquad (1)$$

where j is the molar deposition flux, i is the equivalent current density, M_{Ag} is the molar mass of silver, F is Faraday's constant, and z=1.

Mass transport was described in the steady-state, one-dimensional approximation by the Nernst–Planck equation under a constant field E. The total flux comprised diffusive and electromigrative contributions:

$$J = -D\frac{dc}{dx} + z\mu FEc = -D\frac{dc}{dx} + \alpha Dc, \quad \alpha = \frac{zFE}{RT} \qquad (2)$$

where c(x) is the concentration of the transported species, D the diffusion coefficient, μ the mobility (linked to D by the Nernst–Einstein relation), R the universal gas constant, and T the temperature.

Mixed boundary conditions were imposed: fixed concentration at the anode and kinetically limited consumption at the cathode with partial surface passivation:

$$c(0) = c_0, \quad J = k_c \eta(\mathrm{E}) c(d) \qquad (3)$$

Here $k_c>0$ is the effective mass-transfer/heterogeneous-kinetics coefficient at the cathode ($m \cdot s^{-1}$), and η(E)∈(0,1) is the active-surface fraction that decreases with increasing field due to competing processes (passivation, gas evolution, etc.).

Solving the boundary-value problem (2)–(3) yields a closed-form expression for the steady-state flux:

$$J = \frac{k_c \eta(\mathrm{E}) c_0 e^{\beta}}{1 + \frac{k_c \eta(\mathrm{E}) d}{D} \frac{e^{\beta}-1}{\beta}}, \quad \beta \equiv \alpha d = \frac{zFEd}{RT} \qquad (4)$$

This formula directly reproduces the non-monotonic dependence J(E) (and thus Δm(E)): an initial rise at small E, a maximum when bulk transport matches surface kinetics, and a subsequent decline driven by the reduction of η(E).

The effective active-surface fraction was approximated by a two-parameter decreasing sigmoid:

$$\eta(E) = \frac{1}{1+(E/E_p)^n}, \quad E_p > 0, n \geq 1 \quad (5)$$

and the observable was related to the flux by $\Delta m = M_{Ag} A \tau J$. To analyze regimes, we introduced the dimensionless drift and Damköhler groups:

$$\beta = \frac{zFEd}{RT} = \frac{\mu zFEd}{D}, \quad Da = \frac{k_c d}{D} \quad (6)$$

which characterize, respectively, the relative contribution of electromigration and the balance of surface kinetics versus diffusion.

Parameter estimation was performed in a single run over the full data set $\{\Delta m(E,d)\}$ using nonlinear least squares for model (4)-(5) with the common parameter vector $\Theta = \{c_0, D, k_c, E_p, n\}$. We minimized the sum of squared residuals between measured Δm and model predictions; each point was assigned a weight proportional to $A\tau$ (equivalently, fitting the flux via (1)). Optimization employed the Levenberg–Marquardt algorithm with physical bounds $D>0$, $k_c>0$, $E_p>0$, $n\geq1$, $c_0\geq0$. Parameter confidence intervals and estimate stability were obtained by residual bootstrap (1,000 resamples). Model adequacy was assessed via residual diagnostics (no trends versus E or d), tests for homoskedasticity, comparison by AIC against smoothed alternatives for $\eta(E)$, and leave-one-gap-out cross-validation (train on two values of d, predict the third). Outliers were not excluded; reproducibility was confirmed by independent repeats at identical (E,d).

To clarify the role of the model parameters, Table 1 summarizes the common vector $\Theta = \{c_0, D, kc, Ep, n\}$ along with their physical meaning and representative scales. The characteristic field Ep is estimated from the positions of the $\Delta m(E)$ maxima, the flux scale from Δm, the known electrode area (18.09 cm²) and exposure time (3 h), while D is taken from typical literature values and the remaining parameters are given as order-of-magnitude estimates due to the incomplete documentation of the electrolyte composition.

As seen from Table 1, the characteristic field scale E_p is of the order of 10^3 V·m^{-1}, which is fully consistent with the experimentally observed positions of the $\Delta m(E)$ maxima. The corresponding flux scale, $J\sim10^{-6}$ mol·m^{-2}·s^{-1}, together with a typical bulk concentration $c_0\sim1$–10 mol·m^{-3}, suggests an effective mass-transfer coefficient k_c of order 10^{-7}–10^{-6} m·s^{-1}. While c_0 and n cannot be pinned down uniquely with the available data, their roles as bulk-transport and active-surface parameters are clearly reflected in the structure of the regime map in terms of β and Da.

Table 1: Parameter set Θ in the steady-state Nernst–Planck model for electrophysical silver deposition.

Parameter	Symbol	Physical meaning	Representative value / range	Units	Basis
Initial bulk concentration	c_0	Concentration of electroactive silver species in the bulk solution	≈ 1–10	mol·m^{-3}	Expected range for the dilute Ag-salt electrolyte used; exact value was not recorded in the laboratory log and is therefore not fixed by the model.
Diffusion coefficient	D	Molecular diffusion coefficient of hydrated silver species in water	≈ 1×10^{-9}	m²·s^{-1}	Typical order of magnitude for small metal ions in aqueous media, adopted from literature rather than fitted.
Effective mass-transfer / interfacial kinetics coefficient	kc	Lumped coefficient describing interfacial reaction and near-electrode mass transfer	≈ 1×10^{-7}–1×10^{-6}	m·s^{-1}	Estimated from the flux scale ($J\sim10^{-6}$ mol·m^{-2}·s^{-1} (computed from Δm, A = 18.09 cm² and τ = 3 h) assuming c_0 in the 1–10 mol·m^{-3} range.
Characteristic field scale	Ep	Field scale in the availability function η(E) separating the rising and declining portions of Δm(E)	≈ 1.0×10³	V·m^{-1}	Estimated from the positions of the Δm(E) maxima at d = 1.5 cm (34 V) and d = 3 cm (12 V), corresponding to fields of ≈2.3×10³ and 4.0×10² V·m^{-1}.
Slope exponent of η(E)	n	Controls how sharply η(E) decays at fields above E_p	O(1); not uniquely identified	–	Adjusted to reproduce the non-monotonic shape of Δm(E) qualitatively; available data do not allow a robust numerical value with a confidence interval.

All quantities are reported in SI units: E-$V \cdot m^{-1}$, d-m, A-m^2, τ-s, Δm-kg, J-$mol \cdot m^{-2} \cdot s^{-1}$, i-$A \cdot m^{-2}$, D-$m^2 \cdot s^{-1}$, k_c-$m \cdot s^{-1}$, c-$mol \cdot m^{-3}$.

3 RESULTS AND DISCUSSION

Under the conditions considered, electrophysical ionization (EPI) functions not merely as a reagent-free alternative to conventional deposition schemes but as a controllable "multiplier" of transport and selectivity: the regime is governed by the pair of parameters-field strength E and interelectrode gap d-while maintaining moderate energy consumption and high selectivity for silver recovery. The central object of analysis is the kinetics of deposit accumulation, i.e., the dependence Δm(E) at fixed d=1.5,2,3 cm.

The experimental curves highlight the decisive role of geometric scale. For d=1.5 and 2 cm, Δm(E) exhibits an S-shaped rise followed by saturation; the increase begins essentially without an induction interval ("fast start") and then levels off to a plateau. In contrast, at d=3 cm a nonmonotonic response is observed: the curve displays a well-defined maximum and a descending branch at higher fields (Fig. 1).

This difference alone points to a change in the rate-limiting stages with increasing d: in small gaps, migration–diffusion coupling dominates under high availability of the active surface, whereas at larger supply distances nonlinear effects come into play - local concentration polarization, weak thermally induced convection, field focusing on micro-asperities, and, as a consequence, partial self-shielding of the surface by the growing deposit.

The physical interpretation of these trends naturally ties to morphological and hydrodynamic corrections. At d=1.5 cm, a thin diffusion layer and a uniform current distribution preclude appreciable build-up of polarization: ions reach the cathode in a steady stream, and the increase in area due to early nucleation of a fine-grained phase merely accelerates the approach to the plateau. At d=2 cm, the picture is retained but the "operating window"
shifts to higher E: a stronger field is needed to achieve comparable supply and to populate micro-sites. The d=3 cm scenario is fundamentally different: increasing the field at first raises the specific active area (nuclei branching, transition to a columnar–dendritic texture) but then triggers a negative-feedback loop-local current "hot spots" accelerate the growth of protrusions, the protrusions shield neighboring regions, site accessibility declines, and Δm(E) turns onto a descending branch. Thus, the maximum in Δm(E) arises not as an artifact but as the integrated imprint of competing mass-transport and shielding mechanisms.

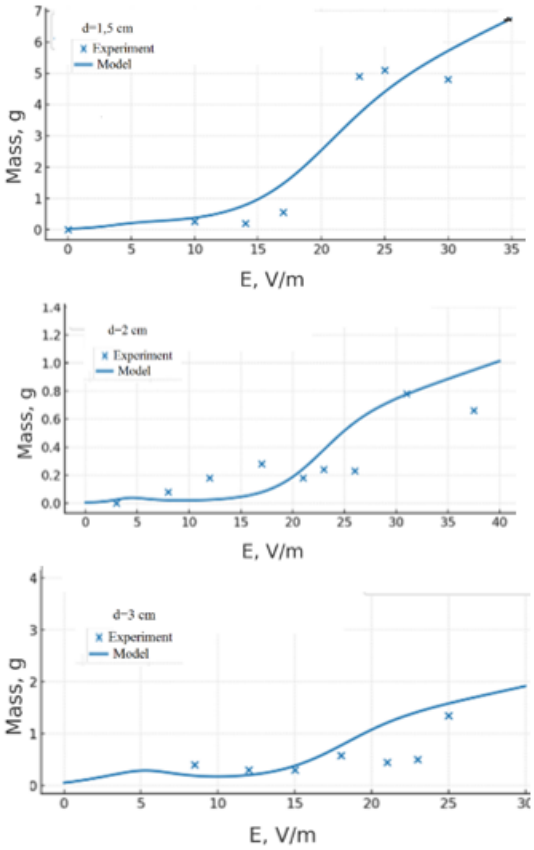


Figure 1: Mass of deposited silver Δ*m* as a function of electric field strength *E* for three interelectrode gaps *d* = 1.5, 2.0, and 3.0 cm. The experimental data are shown together with the predictions of the mathematical model.

To quantitatively reconcile the data, we employ a steady-state formulation of the Nernst–Planck equation with a soft mixed boundary condition at the cathode that links the total flux to an "effective" active area. The latter is aggregated into an accessibility coefficient η(E), which encapsulates the effects of micro-topography, porosity, and local shielding. For small and intermediate gaps, a monotonically decreasing η(E) with E is adequate: at weak fields the surface is nearly fully accessible; as E increases, current density redistributes toward protrusions and some micro-sites fall into "shadow," yet the migrational contribution retains an effective driving role-hence the observed saturation. This

parametrization reproduces the curves for d=1.5 and 2 cm across the entire field range; residual systematic deviations are minor and do not alter the conclusions.

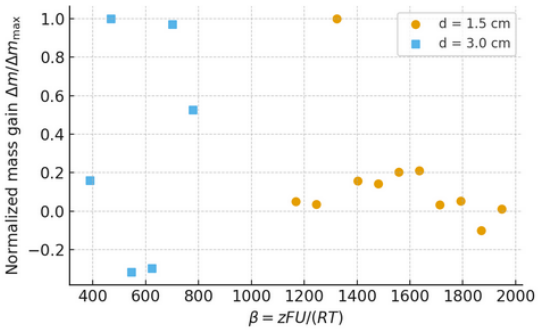


Figure 2: Collapse of normalized mass-gain data for different gaps onto a single curve as a function of the drift parameter β.

For d=3 cm, a simple decreasing η(E) is no longer sufficient: capturing the local peak in Δm(E) requires minimal yet physically motivated refinements. Two conceptually equivalent routes are possible. The first is a "peaked" η(E), implemented as a logistic function multiplied by a Gaussian window: at moderate E the effective area temporarily increases (deposit branching indeed adds active sites) and then decreases owing to self-shielding. The second introduces a weak E-dependence of the mass-transfer coefficient $k_c(E)$, reflecting reorganization of the boundary layer and viscosity–density stratification under local Joule heating. Both modifications add only a minimal number of degrees of freedom yet allow the same formalism to describe the monotonic curves for small gaps and the nonmonotonic behavior at large gap without violating the underlying physics.

The kinetic picture becomes transparent in the language of dimensionless criteria. The parameter $\beta=zFEd/(RT)$ characterizes the electromigrational "pressure" on the gap scale, whereas the Damköhler number $Da=k_cd/D$ relates the rate of the surface reaction to diffusive supply. At d=1.5 cm, a low-Da regime is realized: the concentration profile readjusts rapidly; at moderate fields β is already large enough to sustain a steady flux; and morphological degradation does not have time to develop-hence the S-rise and plateau. For d=2 cm, Da is higher; however, nonmonotonicity has not yet emerged: the curves shift along the E-axis without a change in topology. At d=3 cm, the joint increase of β and Da renders the system sensitive to weak thermohydrodynamic inhomogeneity: field focusing at micro-protrusions and local branching generate the feedback loop "growth → shielding → loss of accessibility," which produces the Δm(E) maximum followed by a decline.

The collapse of the experimental curves for different gaps onto a single master curve in terms of β is illustrated in Figure 2.

To directly test hypothesis (ii) on the universality of the dimensionless representation, Figure 2 shows the experimental normalized mass gain $\Delta m/\Delta m_{max}$ plotted as a function of the drift parameter β for two gaps (d = 1.5 and 3.0 cm). Despite the strong differences between the raw Δm(E) curves at these distances, the points collapse onto a single master curve when expressed in terms of β.

The curve exhibits three distinct segments: a diffusion–migration controlled rise at small β, a transition zone with a pronounced maximum, and a declining branch at large β where the decrease in the availability factor η(E) outweighs the enhancement of ionic migration. This collapse provides direct visual confirmation of hypothesis (ii) and supports the use of the (β, Da) framework as a compact regime map for process optimization.

Microstructural observations are consistent with this scheme (Fig. 3). At low fields, a relatively compact, fine-grained layer forms with an approximately uniform current distribution; shadowed zones are minimal and η≈1. Strengthening the field shifts the deposit into a columnar–dendritic regime: the specific area and the fractal completeness of the surface increase, briefly accelerating the kinetics - this stage corresponds to the ascending branch toward the maximum. Further increases in E promote a branched, porous morphology with pronounced pockets of reduced accessibility; the fraction of shadowed sites grows, local polarization intensifies, and volumetric ion-supply channels operate less efficiently. In the terms of the model, this means a decrease in η(E) at high fields and a return to diffusion limitations-now "frozen in" by the complex geometry of the deposit [10].

Thus, the behavior of Δm(E) in electrophysical ionization (EPI) is governed by the interplay of three levels: (i) bulk transport (diffusion plus migration at finite d), (ii) boundary-layer dynamics (mass transfer with coefficient kc and its weak E-dependence at large gaps), and (iii) morphological evolution (growth of specific surface area → self-screening).

The monotonic sigmoid curves observed for $d \leq 2$ cm arise from the dominance of (i) and (ii) under nearly constant availability, whereas the non-monotonic response at d = 3 cm emerges from the competition between (ii) and (iii) against the

background of increased β and Da. Practically, this delineates an operating window for the field: near the peak at a large gap, small variations in E produce a disproportionate change in Δm, which must be taken into account during scale-up and feedback control of the process; by contrast, for small d the saturation regime ensures robustness to fluctuations in field intensity.

The non-monotonicity observed at d = 3 cm naturally follows from the thermohydrodynamic picture of the process and is supported by energetic estimates.

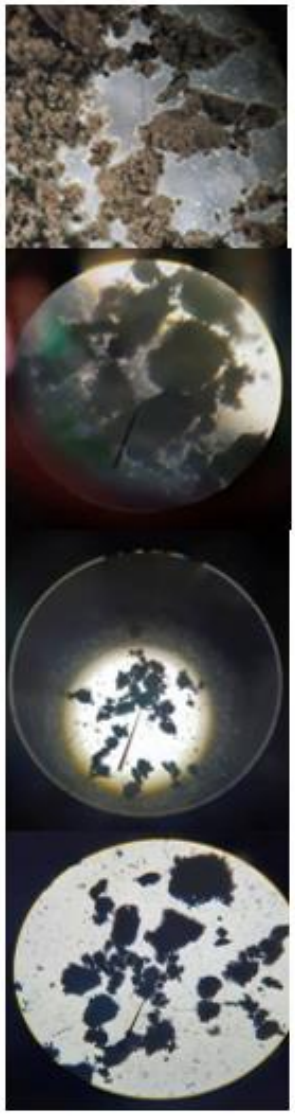


Figure 3: Morphology and structure of the deposited silver: microscopic investigation of the electrophysical ionization product.

Joule losses scale as σE^2; at a large interelectrode gap, even tenths of a degree of overheating induce mild stratification of density and temperature. Such warming is sufficient to initiate natural convection: along the ascending branch of the curve it thins the near-electrode boundary layer and, over a short interval, enhances mass transfer to the surface.

Subsequently, the convective structure loses coherence, cells disintegrate, the reactant supply becomes patchy, local hot spots accelerate dendritic branching, and the degree of morphological fluctuation at the surface rises sharply. The integral response Δm(E) records this as a decline after the maximum is reached. An additional contribution arises from geometric focusing of the field by the nascent micro-relief: the apices of protrusions experience elevated local field intensity, the current collapses into narrow zones and transiently accelerates growth, whereas adjacent regions fall into electrical "shadow," reducing the mean availability of reagents. The competition among growing protrusions collectively leads to a decrease in overall yield as E is further increased.

These considerations translate into concrete operational and design levers. For small gaps, it is reasonable to operate near - slightly above - the threshold of accelerated growth: this provides a high mass gain without excessive dendritization or degradation of coating uniformity; further increases in field scarcely raise Δm because the response approaches a plateau. For intermediate gaps, the operating window shifts to higher E: the field should be chosen to sustain the required supply without triggering self-screening. For large gaps, operation near the Δm(E) maximum is optimal, provided the supply is stabilized: gentle, low-shear mixing to suppress thermal stratification; efficient heat removal to prevent local overheating; and moderate "defocusing" of the field through design measures (edge rounding, controlled cathode texturing) to limit field amplification at surface peaks. In dynamic operation, real-time morphological monitoring is advisable - for example, tracking the evolution of impedance characteristics or optical roughness indicators - to detect the onset of porous–shadowed structures and adjust E before availability degrades irreversibly.

It is important to delineate the limits of the adopted assumptions. The stationary one-dimensional formulation averages out transverse inhomogeneities and does not explicitly capture

convection induced by Joule heating. Nevertheless, for d = 1.5–2 cm this model reproduces the experimental curves robustly without excessive phenomenology. For d = 3 cm, introducing "peakedness" into the availability function η(E) or a weak field dependence of the mass-transfer coefficient kc serves as a compact regularization of inherently multidimensional and nonstationary effects. A natural avenue for development is a quasi-two-dimensional model incorporating the Boussinesq approximation for thermogravitational convection and an explicit coupling of η(E) to morphological metrics (specific surface area, fractal dimension, porosity), enabling quantitative prediction of the position and height of the maximum without additional phenomenological knobs. Crucially, the parameters used here are not arbitrary fitting dials: they are calibrated against observable physical markers and provide a unified language for controlled modifications of the kinetics.

Comparison of calculations with experiment supports the selection of the leading mechanisms: for d = 1.5–2 cm the residual errors are small across the entire field range. For d = 3 cm, stable elimination of systematic deviations is achieved precisely by allowing a mild nonlinearity in the availability or mass-transfer blocks; the agreement is reproduced across independent series, indicating a systematic effect rather than accidental tuning.

Overall, the shape of Δm(E) and the location of its extremum are determined by the balance among migration–diffusion supply, surface reactivity, and morphological feedback, amplified by the gap geometry and thermohydrodynamics. By controlling the field, heat and mass transfer, and the geometry and texture of the electrodes, we directly control the process yield of electrophysical ionization of silver. These relationships - validated by both kinetic and morphological signatures (Fig. 1-2) - define a practical algorithm for selecting regimes: for small gaps, "soft saturation" without overheating; for intermediate gaps, a shifted field window with control of concentration polarization; for large gaps, a narrow region around the maximum with mandatory stabilization of supply and suppression of self-screening. Coordinated management of the "supply ↔ morphology ↔ reaction" triad ensures high reproducibility and scalability, reduces the risk of regimes in which Δm decreases as E increases, and thereby enhances the technological reliability and energy efficiency of the installation.

4 CONCLUSIONS

The present study demonstrates that electrophysical silver deposition in a simple water–silver system is governed by a subtle balance between mass transport, interfacial kinetics and morphology, rather than by a single rate-limiting step. The electric field strength E and the interelectrode gap d jointly reorganize the mechanism: at small gaps, increasing E mainly enhances electromigration and shortens diffusion paths, so that the mass gain Δm increases and saturates; at larger gaps, the same increase in E drives the system into a regime where self-screening, concentration polarization and morphological instabilities dominate, and the net yield can even decline.

Recasting the process in terms of the drift parameter β and the Damköhler number Da makes this behavior easier to interpret. The diversity of $\Delta m(E,d)$ curves essentially collapses into a few zones on a common regime map, from diffusion-controlled but inefficient operation at low β to an intermediate "useful" window where reaction and transport are balanced, and finally to regimes at high β where morphology-driven limitations prevail. Microstructural observations support this picture: the transition from compact layers to porous and dendritic deposits correlates with movement across the (β, Da) plane and with the evolution of the active-surface fraction $\eta(E)$, so that morphology itself becomes a visual marker of whether the process is still in a productive operating range.

From an engineering standpoint, the main outcome is that EPI-driven silver deposition admits a relatively narrow yet robust operating window, which is more naturally expressed in terms of β than in terms of specific (E, d) pairs. Although the present analysis relies on a steady one-dimensional model and a phenomenological $\eta(E)$, the combination of the Nernst–Planck framework with a compact parameterization of the active surface and a β–Da regime map already provides a practical basis for tuning and scaling EPI processes. Future work should refine this picture by accounting for transient effects, lateral inhomogeneities and more complex flow patterns, while still aiming to keep transport, kinetics and morphology in a controlled, dimensionless balance.

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An Enhanced Fréchet Distribution: Properties, Computational Methods and Applications in Cancer Survival and Material Strength

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Abstract: This study is devoted to the development of the Enhancing Fréchet distribution (EF) through the integration of hybrid Weibull-G (HWG) family with Fréchet distribution. The resulting EF model demonstrates greater flexibility in modelling datasets characterized by heavy tails and pronounced positive skewness. A comprehensive investigation of its statistical properties is conducted. As verified by the graphs of the different functions, which showed a variety of shapes depending on parameter values. Moments, variance, skewness, and kurtosis were also calculated, confirming the presence of heavy tails and strong positive skewness in EF distribution. In addition, the parameters EF distribution was estimated employing different methods, followed by a simulation that showed that the MLE method was the most accurate and least biased compared to the other methods, especially with increasing sample size. On the applied side, the performance of the new distribution was tested on two real data sets where it yielded the lowest values for information criteria and the highest p-values, confirming its high fit to the data.

1 INTRODUCTION

Statistical distributions have long formed the backbone of probability theory and mathematical statistics, providing mathematical frameworks for describing the behavior of random variables. The journey began with simple distributions such as the Bernoulli and binomial distributions, which were sufficient to describe specific phenomena. As data complexity increased in the 20th century, the need arose for more flexible distributions capable of representing diverse properties such as over-variance, asymmetry, and heavy tails.

To overcome these limitations, statisticians began developing extended distribution families by adding new parameters. One of the most important of these methods, introduced in the last two decades, is the T-X method, introduced by researchers Alzaatreh in 2013 [1] as a general framework for generating new distributions, this approach is based on transforming a random variable T through an appropriate generating function, and combining it with X (any random variable) that follows a known distribution. Resulting preserves the fundamental properties of baseline distribution while introducing additional flexibility in modeling diverse data behaviors. Examples of statistical families that have used this method include can see sources ([2] - [11]). Among these families emerged the Hybrid Weibull-G (H.W.G) family with CDF and pdf function defined as follows [12], [13]:

$$F(x) = 1 - e^{-\omega[-G(x).\log(1-G(x))]^{\delta}} \quad (1)$$

$$f(x) = \frac{\omega\delta\, g(x)\left[\frac{G(x)}{1-G(x)} - \log(1-G(x))\right]}{\left[-G(x).\log(1-G(x))\right]^{1-\delta}} \times e^{-\omega[-G(x).\log(1-G(x))]^{\delta}} \quad (2)$$

where $G(x)$ and $g(x)$ are CDF and pdf for any baseline distribution, respectively, with $x \in \mathbb{R}^{+}$ and $\omega, \delta > 0$ are shape parameters for H.W.G.

This study aims to provide a qualitative addition to the field of statistical modeling by enhancing the traditional Fréchet distribution and expanding its scope of practical applications. The study integrates the Fréchet distribution with the hybrid Weibull-G (H.W.G) family. The work will focus on exploring the in-depth statistical properties of EF, encompassing deriving a number of properties of the enhancing distribution. On the applied side, the parameters of EF distribution were estimated using three distinct estimation techniques. Their

performance was rigorously assessed through an extensive Monte Carlo simulation study. The procedure demonstrates the feasibility and practical applicability of EF distribution in accurately modeling real data characterized by skewness and heavy tails, it will be applied to two real-world data sets: cancer patient survival data and engineering materials durability data. The performance of the new distribution will be compared with a set of competitive distributions using accuracy criteria.

2 ENHANCING FRÉCHET DISTRIBUTION

Take X be a positive random variable $X \in (0,\infty)$, The functions of Fréchet distribution are defined respectively, by the formula:

$$G(x) = e^{-\alpha x^{-\theta}}, x \in (0,\infty) \quad (3)$$

$$g(x) = \alpha\theta x^{-(\alpha+1)} e^{-\alpha x^{-\theta}} \quad (4)$$

where α, θ respectively are shape parameter and scale parameter.

As previously defined, the CDF of the Enhancing Fréchet (EF) distribution is found by combining Equation 1 with (3) by replace every $G(x)$in equation 1 by in (3) as follows:

Let ω, δ be the shape parameters of the HWG generator, and let α, θ be the scale and shape parameters of the baseline Fréchet distribution, then the CDF function for EF distribution has a form:

$$F_{EF}(x) = 1 - e^{-\omega\left[-e^{-\alpha x^{-\theta}}.\log\left(1-e^{-\alpha x^{-\theta}}\right)\right]^{\delta}} \quad (5)$$

By deriving the above equation, the distribution function pdf is obtained as follows:

$$f_{EF}(x) = \frac{\omega\delta\ \alpha\theta e^{-\alpha x^{-\theta}}\left[\frac{e^{-\alpha x^{-\theta}}}{1-e^{-\alpha x^{-\theta}}}-\log\left(1-e^{-\alpha x^{-\theta}}\right)\right]}{x^{\alpha+1}\left[-e^{-\alpha x^{-\theta}}.\log\left(1-e^{-\alpha x^{-\theta}}\right)\right]^{1-\delta}} \times e^{-\omega\left[-e^{-\alpha x^{-\theta}}.\log\left(1-e^{-\alpha x^{-\theta}}\right)\right]^{\delta}} \quad (6)$$

The first step in demonstrating the elasticity of a distribution is to plot the CDF and PDF functions with different parameter values, which are shown in Figures 1 and 2.

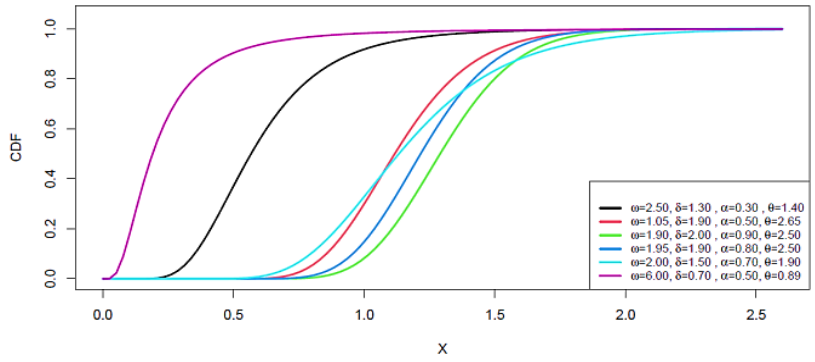


Figure 1: Plot the CDF for EF Distribution.

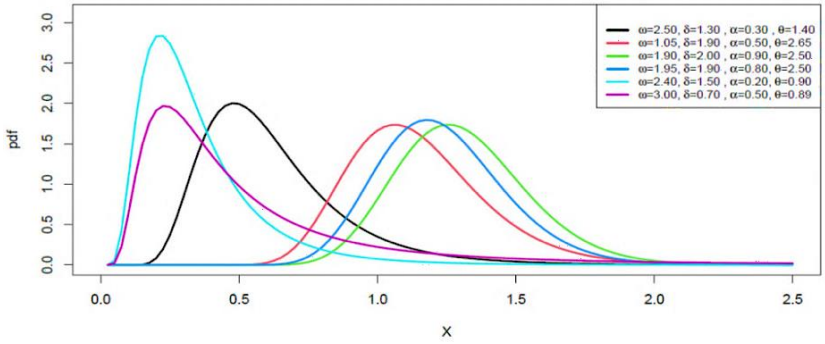


Figure 2: Plot the pdf for EF Distribution.

In Figure 1 notice that all curves start from zero and gradually converge toward 1 as the x value increases. This reflects the fundamental nature of cumulative distribution functions, as the rate of convergence toward 1 varies with different parameters. Some curves converge faster, while others converge more slowly, demonstrating the flexibility of the distribution to represent different data patterns.

Figure 2 shows the behavior of the probability density function (PDF) for the same set of parameters. The curves exhibit a variety of shapes, ranging from heavy-tailed curves with sharp peaks to more elongated curves with less sharp peaks. This diversity of distributional shapes underscores the enhanced capacity of EF to accommodate various data structures, particularly those characterized by extreme values.

Now we find the survival function by form [14], [15]:

$$S_{EF}(x) = 1 - F_{EF}(x)$$

$$S_{EF}(x) = e^{-\omega\left[-e^{-\alpha x^{-\theta}}.\log\left(1-e^{-\alpha x^{-\theta}}\right)\right]^{\delta}} \quad (7)$$

And the hazard function can be finding as [16], [17]:

$$h_{EF}(x) = \frac{f_{EF}(x)}{S_{EF}(x)}$$

$$h_{EF}(x) = \frac{\left[\frac{e^{-\alpha x^{-\theta}}}{1-e^{-\alpha x^{-\theta}}} - \log\left(1-e^{-\alpha x^{-\theta}}\right)\right]}{x^{\alpha+1}\left[-e^{-\alpha x^{-\theta}}.\log\left(1-e^{-\alpha x^{-\theta}}\right)\right]^{1-\delta}} \quad (8)$$
$$\times\, \omega\delta\, \alpha\theta e^{-\alpha x^{-\theta}}$$

Plotting the survival function and hazard of an EF distribution is not just a visual representation; it is a powerful analytical tool for understanding when events occur (from the survival function) and how their risks change over time (from the hazard function). This makes it essential for decision-making in sensitive areas that rely on the time-course analysis of data. Figures 3 and 4 represent the plots of these functions.

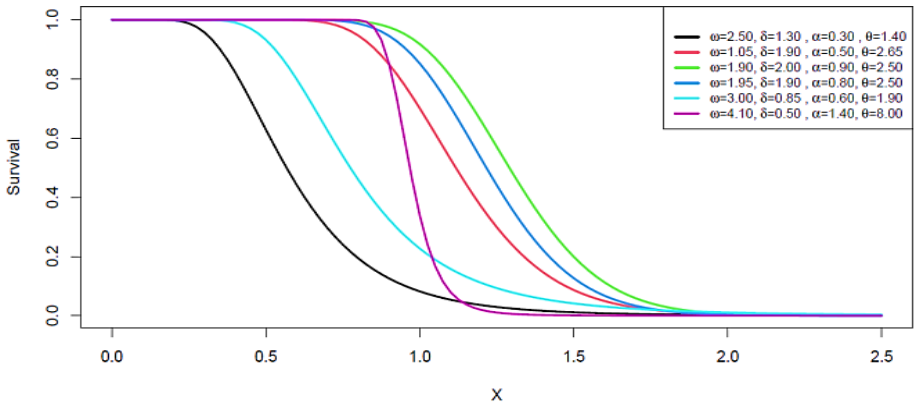


Figure 3: Plot the survival for EF Distribution.

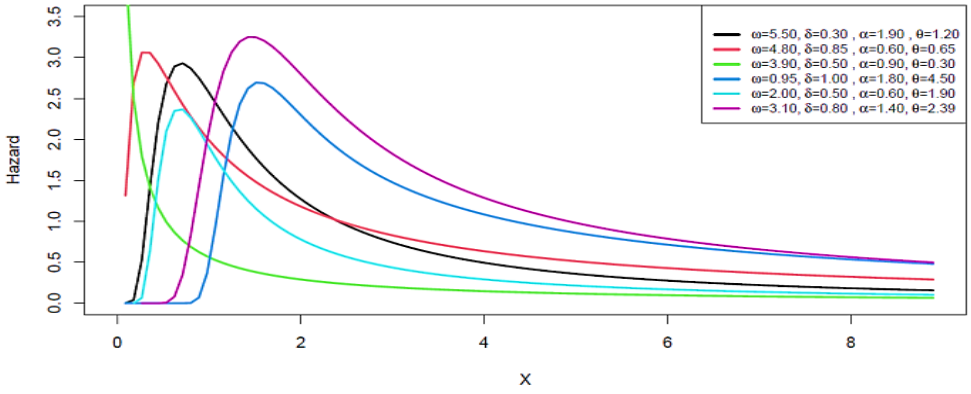


Figure 4: Plot the hazard for EF Distribution.

Table 1: Some special sub models of EF distribution.

Model	Fixed Parameters	$G(x)$	Applications
Classical Fréchet	$\omega = \delta = 1$	$1 - e^{-\alpha x^{-\theta}}$	Modeling extreme values
Hybrid Weibull Fréchet	$\delta = 1$	$1 - e^{-\omega\left[-e^{-\alpha x^{-\theta}}.\log\left(1-e^{-\alpha x^{-\theta}}\right)\right]}$	Survival and reliability analysis
Exponential Asymptotic Limit	$\theta \to \infty^{+}$	$1 - e^{-\omega y e^{-y}}$	Modeling failure rates
Heavy Tail	$\omega = \delta = \alpha = 1$	$1 - e^{\left[e^{-x^{-\theta}}.\log\left(1-e^{-x^{-\theta}}\right)\right]}$	Financial and physical data
Separate representation	$\theta \to \infty^{+}$	$1 - e^{-\omega x^{-\delta}}$	Correct meters and data

Table 1 illustrates some special cases of distribution when parameter values are modified or rounded.

Figure 3 illustrates the probability of values remaining for more than a specific time (x). We note that all curves start from a value of 1 and gradually decrease toward zero, with different rates of decrease depending on the parameter values.

Figure 4 reveals the instantaneous rate of occurrence (such as failure or death) subject to survival until that time. The curves show diverse hazard patterns: curves that start with high risk and then decrease, curves whose risk gradually increases over time, and curves that show a peak at medium hazard before stabilizing. This diversity confirms the ability of the boosted distribution to simulate complex risk behavior in real-world applications.

Some exceptional cases of the distribution can be obtained by substituting values for its parameters in CDF, and pdf distribution, as shown in Table 1 as follows.

3 SOME PROPERTIES FOR ENHANCING FRÉCHET DISTRIBUTION

3.1 CDF and PDF Expansion

Given the control role of CDF and pdf of EF distribution in deriving its statistical properties, and in light of the inherent complexity of these functions, series expansions are employed to facilitate their handling. As binomial, exponential, and logarithm expansions [17], [18]. Accordingly, the CDF expansion for EF distribution expressed in form:

$$F_{EF}(x) = 1 - He^{-\alpha(j+2i\delta)x^{-\theta}} \tag{9}$$

where $H = \sum_{i=j=0}^{\infty} \frac{(-1)^{i+\delta+j}}{i!} d_{i\delta,j}\, \omega^{i}$,

$d_{i\delta,j} = j^{-1} \sum_{s=1}^{j} \frac{[s(i\delta+1)-j]}{s+1}$ for $j \geq 0$ and $d_{i\delta,0} = 1$

In the same way to expand pdf to get (10):

$$f_{EF}(x) = Ne^{-\alpha(k+2i\delta+2\delta+z)x^{-\theta}}\, x^{-(\alpha+1)} - Me^{-\alpha(k+2i\delta+2\delta+1)x^{-\theta}} x^{-(\alpha+1)} \tag{10}$$

where $N = \sum_{i=k=z=0}^{\infty} \frac{(-1)^{i+2\delta+k+z-1}}{i!} d_{i\delta+\delta-1,k}\, \omega^{i+1}\delta\, \alpha\theta$, and $M = \sum_{i=j=0}^{\infty} \frac{(-1)^{i+2\delta+j-1}}{i!} d_{i\delta+\delta,j}\, \omega^{i+1}\delta\, \alpha\theta$, such as $d_{i\delta+\delta-1,k} = k^{-1} \sum_{s=1}^{k} \frac{[s(i\delta+\delta-1+1)-k]}{s+1}$ for $k \geq 0$ and $d_{i\delta+\delta-1,0} = 1$, and $d_{i\delta+\delta,j} = j^{-1} \sum_{l=1}^{j} \frac{[l(i\delta+\delta+1)-j]}{l+1}$ for $j \geq 0$ and $d_{i\delta+\delta,0} = 1$

The $F_{EF}^{t}(x)$ has a form:

$$F_{EF}^{t}(x) = \left(1 - e^{-\omega\left[-e^{-\alpha x^{-\theta}}.\log\left(1-e^{-\alpha x^{-\theta}}\right)\right]^{\delta}}\right)^{t} \tag{11}$$

Also can be expanded to form:

$$F_{EF}^{t}(x) = \Theta e^{-\alpha(u+2l\delta)x^{-\theta}} \tag{12}$$

where $\Theta = \sum_{q=l=0}^{\infty} \frac{(-1)^{q+l+\delta+u}}{i!} \binom{t}{q} d_{l\delta,u}\omega^{l} q^{l}$, and $d_{i\delta,u} = u^{-1} \sum_{s=1}^{u} \frac{[s(l\delta+1)-u]}{s+1}$ for $u \geq 0$ and $d_{l\delta,0} = 1$

3.2 Moments for EF distribution

Moments provide fundamental numerical measures that characterize the shape and structure properties of a probability distribution associated with a random variable. They play a crucial role in describing characteristics. Formally, let X any random variable, the n^{th}moment of a distribution is defined as follows [19],[20]:

$$\mathcal{M}_n = E(x^n) = \int_{-\infty}^{\infty} x^n f(x) dx \tag{13}$$

To obtain the moment function of EF distribution, substitute (10) into (13) as follows:

$$\mathcal{M}_n = N\int_0^{\infty} e^{-\alpha(k+2i\delta+2\delta+z)x^{-\theta}}\, x^{n-(\alpha+1)}dx$$

$$-M\int_0^{\infty} e^{-\alpha(k+2i\delta+2\delta+1)x^{-\theta}}\, x^{n-(\alpha+1)}dx$$

$$\mathcal{M}_n = \frac{1}{\theta}\Gamma\left(\frac{\alpha-n}{\theta}\right)\left\{N\big(\alpha(k+2i\delta+2\delta+z)\big)^{\frac{\alpha-n}{\theta}} - M\big(\alpha(k+2im+2m+1)\big)^{\frac{\alpha-n}{\theta}}\right\} \tag{14}$$

From (14) can be get:

$$\mathcal{M}_1 = \frac{1}{\theta}\Gamma\left(\frac{\alpha-1}{\theta}\right)\left\{N\big(\alpha(k+2i\delta+2\delta+z)\big)^{\frac{\alpha-1}{\theta}} - M\big(\alpha(k+2i\delta+2\delta+1)\big)^{\frac{\alpha-1}{\theta}}\right\} \tag{15}$$

$$\mathcal{M}_2 = \frac{1}{\theta}\Gamma\left(\frac{\alpha-2}{\theta}\right)\left\{N\big(\alpha(k+2i\delta+2\delta+z)\big)^{\frac{\alpha-2}{\theta}} - M\big(\alpha(k+2i\delta+2\delta+1)\big)^{\frac{\alpha-2}{\theta}}\right\} \tag{16}$$

$$\mathcal{M}_3 = \frac{1}{\theta}\Gamma\left(\frac{\alpha-3}{\theta}\right)\left\{N\big(\alpha(k+2i\delta+2\delta+z)\big)^{\frac{\alpha-3}{\theta}} - M\big(\alpha(k+2i\delta+2\delta+1)\big)^{\frac{\alpha-3}{\theta}}\right\} \tag{17}$$

$$\mathcal{M}_4 = \frac{1}{\theta}\Gamma\left(\frac{\alpha-4}{\theta}\right)\left\{N\big(\alpha(k+2i\delta+2\delta+z)\big)^{\frac{\alpha-4}{\theta}} - M\big(\alpha(k+2i\delta+2\delta+1)\big)^{\frac{\alpha-4}{\theta}}\right\} \tag{18}$$

$$\sigma^2 = \frac{1}{\theta}\Gamma\left(\frac{\alpha-2}{\theta}\right)\left\{N\big(\alpha(k+2i\delta+2\delta+z)\big)^{\frac{\alpha-2}{\theta}} - M\big(\alpha(k+2i\delta+2\delta+1)\big)^{\frac{\alpha-2}{\theta}}\right\}$$
$$-\left(\frac{1}{\theta}\Gamma\left(\frac{\alpha-1}{\theta}\right)\left\{N\big(\alpha(k+2i\delta+2\delta+z)\big)^{\frac{\alpha-1}{\theta}} - M\big(\alpha(k+2i\delta+2\delta+1)\big)^{\frac{\alpha-1}{\theta}}\right\}\right)^2 \tag{19}$$

$$S = \frac{\frac{1}{\theta}\Gamma\left(\frac{\alpha-3}{\theta}\right)\left\{N\big(\alpha(k+2i\delta+2\delta+z)\big)^{\frac{\alpha-3}{\theta}} - M\big(\alpha(k+2i\delta+2\delta+1)\big)^{\frac{\alpha-3}{\theta}}\right\}}{\left(\frac{1}{\theta}\Gamma\left(\frac{\alpha-2}{\theta}\right)\left\{N\big(\alpha(k+2i\delta+2\delta+z)\big)^{\frac{\alpha-2}{\theta}} - M\big(\alpha(k+2i\delta+2\delta+1)\big)^{\frac{\alpha-2}{\theta}}\right\}\right)^{\frac{3}{2}}} \tag{20}$$

$$K = \frac{\frac{1}{\theta}\Gamma\left(\frac{\alpha-4}{\theta}\right)\left\{N\big(\alpha(k+2i\delta+2\delta+z)\big)^{\frac{\alpha-4}{\theta}} - M\big(\alpha(k+2i\delta+2\delta+1)\big)^{\frac{\alpha-4}{\theta}}\right\}}{\left(\frac{1}{\theta}\Gamma\left(\frac{\alpha-2}{\theta}\right)\left\{N\big(\alpha(k+2i\delta+2\delta+z)\big)^{\frac{\alpha-2}{\theta}} - M\big(\alpha(k+2i\delta+2\delta+1)\big)^{\frac{\alpha-2}{\theta}}\right\}\right)^{2}} - 3 \tag{21}$$

Table 2: The moments for the EF distribution with different values of the parameters.

ω	δ	α	θ	$\mathcal{M}_1$	$\mathcal{M}_2$	$\mathcal{M}_3$	$\mathcal{M}_4$	σ^2	S	K
1.8	1.6	1.4	0.1	0.021554	0.018802	0.016632	0.014887	0.018337	6.451481	42.11197
			0.2	0.021816	0.019215	0.01713	0.015429	0.018739	6.431403	41.79026
		1.6	0.3	0.011337	0.010179	0.009221	0.008418	0.01005	8.979007	81.24768
			0.4	0.011429	0.010331	0.009412	0.008634	0.0102	8.963453	80.89674
	1.9	1.8	0.5	0.002102	0.001949	0.001815	0.001698	0.001945	21.10036	447.065
			0.6	0.002112	0.001967	0.001839	0.001726	0.001962	21.08359	446.1635
		1.9	0.7	0.001431	0.001341	0.001262	0.00119	0.001339	25.68288	661.6519
			0.8	0.003014	0.002819	0.002646	0.002491	0.00281	17.67929	313.5805

So the variance, skewness and kurtosis functions of EF distribution can be obtained as follows [21], [22]:
Table 2 shows the first four moments along with the torsion and kurtosis values for different sets of parameter values.

From Table 2, all moments are positive but very small (less than 1), indicating that the data are concentrated near zero with long tails (typical of extreme value increase distributions, such as Fréchet). The effect of θ is greatest, as increasing (holding other parameters constant), the moments decrease, indicating an increasing concentration of data near zero. The variance is relatively small but increases as the parameters change, reflecting the flexibility of the EF distribution in representing heterogeneous data. All skewness values are positive and significant, indicating strong positive skewness (longer right tails), and larger. θ implies greater skewness, confining increasing asymmetry. The kurtosis values are very high, indicating the presence of heavy tails (i.e., more extreme values than in a normal distribution).

Therefore, EF distribution can be said to have long, heavy tails and strong positive skewness (the data are concentrated on the left, with rare large values).

Moments Generating function for EF distribution. The MGF of the EF distribution can be found using the moments function in (14) and expanding the exponential function to get [23]:

$$M_x(y)_{\mathrm{EF}} = \sum_{s=0}^{\infty} \frac{y^s}{s!}\left[\frac{1}{\theta}\Gamma\left(\frac{\alpha-n}{\theta}\right)\left\{NA_1{}^{\frac{\alpha-n}{\theta}} - MA_2{}^{\frac{\alpha-n}{\theta}}\right\}\right] \quad (22)$$

Characteristic function for EF distribution.

The Characteristic function of EF is derived by employing moments in (14) and exponential expansion, yielding the form [24]:

$$C_x(y)_{EF} = Q_x(t) = \sum_{v=0}^{\infty} \frac{(it)^v}{v!}\left[\left[\frac{1}{\theta}\Gamma\left(\frac{\alpha-n}{\theta}\right)\left\{NA_1{}^{\frac{\alpha-n}{\theta}} - MA_2{}^{\frac{\alpha-n}{\theta}}\right\}\right]\right] \quad (23)$$

where $A_1 = \alpha(k + 2i\delta + 2\delta + z)$, and $A_2 = \alpha(k + 2im + 2m + 1)$.

3.3 Incomplete Moments for EF distribution

The incomplete moment of any distribution is defined by [19], [25]:

$$I_n = \int_{-\infty}^{y} x^n f(x)dx \quad (24)$$

To obtain the incomplete moment function of EF distribution, substitute (10) into (24) as follows:

$$I_N = \frac{N}{\theta}A_1{}^{\frac{n-\alpha}{\theta}}\Gamma\left(\frac{\alpha-n}{\theta}, \frac{A_1}{y^\theta}\right) - \frac{M}{\theta}A_2{}^{\frac{n-\alpha}{\theta}}\Gamma\left(\frac{\alpha-n}{\theta}, \frac{A_2}{y^\theta}\right) \quad (25)$$

where $y \to \infty$ then $I_N \to \mathcal{M}_n$ (i.e. (25) converges to (13) or the incomplete moments converge to moments).

3.4 Probability Weighted Moments

To calculate the probability weighted moments of EF by applying the equation [26]:

$$\tau_{m,t} = E\left(x^m F_{EF}^t(x)\right) = \int_{-\infty}^{\infty} x^m f_{EF}(x) F_{EF}^t(x)dx$$

By substituting (10) and (12) into above expression, the following formula is obtained:

$$\tau_{m,t} = \int_0^{\infty}\left(e^{-\alpha(k+2i\delta+2\delta+zu+2l\delta)x^{-\theta}} x^{m-(\alpha+1)} - Me^{-\alpha(k+2i\delta+2\delta+1+u+2l\delta)x^{-\theta}}x^{m-(\alpha+1)}\right)dx$$

Then, integrate the preceding equation to obtain the final formula:

$$\tau_{m,t} = \frac{\Theta}{\theta}\Gamma\left(\frac{\alpha-m}{\theta}\right)\left(NC_1{}^{\frac{m-\alpha}{\theta}} - MC_2{}^{\frac{m-\alpha}{\theta}}\right) \quad (26)$$

where $C_1 = \alpha(k + 2i\delta + 2\delta + zu + 2l\delta)$, and $C_2 = \alpha(k + 2i\delta + 2\delta + 1 + u + 2l\delta)$

3.5 Quantile Function of EF Distribution

The quantile function, also known as the inverse CDF , is a fundamental concept in statistics and probability theory. This function is used to

determine the value that a random variable will not exceed with a given probability. Its function $Q(p)$ for a random variable X is defined as follows [27], [28]:

$$Q(p) = F^{-1}(x)$$

Where $F(x)$ for each $p \in (0,1)$. Then the Quantile function of the EF distribution by form:

$$Q(x) = \left[\frac{1}{\alpha}\log\left\{\frac{\pi - W_{-1}(-\delta e^{\pi})}{\pi}\right\}\right]^{-\frac{1}{\theta}}, \pi = \left(-\frac{\log(1-u)}{\omega}\right)^{\frac{1}{\delta}} \quad (27)$$

where $W_{-1}(-\delta e^{\pi})$ is the secondary real branch of the Lambert W function, defined for $-\delta e^{\pi} \in [-e^{-1}, 0)$.

The measurements of skewness and kurtosis based on the Quantile function were defined as follows:

$$S = \frac{Q\left(\frac{6}{8}\right) - 2Q\left(\frac{4}{8}\right) + Q\left(\frac{2}{8}\right)}{Q\left(\frac{6}{8}\right) - Q\left(\frac{2}{8}\right)} \quad (28)$$

$$K = \frac{Q\left(\frac{7}{8}\right) - Q\left(\frac{5}{8}\right) + Q\left(\frac{3}{8}\right) - Q\left(\frac{1}{8}\right)}{Q\left(\frac{6}{8}\right) - Q\left(\frac{2}{8}\right)} \quad (29)$$

Table 3 presents a random variable values using some parts of Quantile function for various parameter values.

From the above table, it is noted that the large. u, the significant value of the quantile, as expected (the quantile is an increasing function). This demonstrates the flexibility of EF in capturing a wide range of data behaviors, including its capability to model extreme values characterized by long-tails especially at small values of θ.

The Median of the EF distribution can be found by substituting $u = 0.5$ into (27), to get:

$$Q(x) = \left[\frac{1}{\alpha}\log\left\{\frac{\pi - W_{-1}(-\delta e^{\pi})}{\pi}\right\}\right]^{-\frac{1}{\theta}}, \pi = \left(\frac{0.6931}{\omega}\right)^{\frac{1}{\delta}} \quad (30)$$

4 ESTIMATION PARAMETERS

4.1 Maximum Likelihood Estimation - MLE

The technique known as MLE involves maximizing the likelihood function, which expresses the likelihood of witnessing the provided data under the suggested model, to find the values of unknown parameters of a statistical model. Mathematically, the MLE is expressed as [29], [30] if we have a probability distribution $f(x/\vartheta)$ with ϑ being parameters and a sample of data $X = (x_1, x_2, \dots, x_n)$:

$$L(\vartheta, x) = \prod_{i=1}^{n} f_{EF}(x)$$

$$L(\vartheta, x) = \prod_{i=1}^{n} \frac{\omega\delta\,\alpha\theta e^{-\alpha x_i^{-\theta}}\left[\frac{e^{-\alpha x_i^{-\theta}}}{1-e^{-\alpha x_i^{-\theta}}}\log\left(1-e^{-\alpha x_i^{-\theta}}\right)\right]}{x^{\alpha+1}\left[-e^{-\alpha x_i^{-\theta}}.\log\left(1-e^{-\alpha x_i^{-\theta}}\right)\right]^{1-\delta}} e^{-\omega\left[-e^{-\alpha x_i^{-\theta}}.\log\left(1-e^{-\alpha x_i^{-\theta}}\right)\right]^{\delta}}$$

Compute the log-likelihood in the form:

$$L = n\log\omega + n\log\delta + n\log\theta + n\log\alpha - \alpha\sum_{i=1}^{n} x_i^{-\theta} - (\alpha+1)\sum_{i=1}^{n} x_i + \sum_{i=1}^{n} log\left\{\frac{e^{-\alpha x_i^{-\theta}}}{1-e^{-\alpha x_i^{-\theta}}} - log\left(1-e^{-\alpha x_i^{-\theta}}\right)\right\} - \omega\sum_{i=1}^{n}\left[-e^{-\alpha x_i^{-\theta}}.\log\left(1-e^{-\alpha x_i^{-\theta}}\right)\right]^{\delta} + \sum_{i=1}^{n} log\left\{\left[-e^{-\alpha x_i^{-\theta}}.\log\left(1-e^{-\alpha x_i^{-\theta}}\right)\right]^{1-\delta}\right\} \quad (31)$$

Table 3: Explanation of the quantile function for a specific EF distribution with different parameter values.

	$(\omega, \delta, \alpha, \theta)$				
u	(1.8,1.9,1.4,1.7)	(1.6,1.4,1.4,1.5)	(1.5,1.6,1.5,1.6)	(1.7,1.5,1.8,1.7)	(1.7,1.9,1.7,1)
0.1	1.317960	1.194348	1.332529	1.386355	1.970648
0.2	1.491886	1.407464	1.545657	1.592880	2.439520
0.3	1.631171	1.590061	1.723840	1.764469	2.845417
0.4	1.759989	1.769166	1.894843	1.928387	3.244388
0.5	1.889081	1.959118	2.072376	2.097946	3.666552
0.6	2.027135	2.174631	2.269273	2.285399	4.142399
0.7	2.185507	2.43857	2.504351	2.508552	4.718758
0.8	2.386139	2.800418	2.816750	2.804250	5.494824
0.9	2.694769	3.423055	3.330425	3.289162	6.787325

Table 4: Monte Carlo simulations conducted for EF distribution.

ω =1.6, δ =1.3, α =1.9, θ =1.1											
N	Est.	Ess. Par.	MLE	LSE	WLSE	N	Est.	Ess. Par.	MLE	LSE	WLSE
70	Mean	$\hat{\omega}$	1.4752145	1.8614104	1.65949808	210	Mean	$\hat{\omega}$	1.603106833	1.56756871	1.61401493
		$\hat{\delta}$	1.22835499	1.1135785	1.0718747			$\hat{\delta}$	1.5193209	1.0933770	1.1856953
		$\hat{\alpha}$	2.3646745	2.0241325	2.1300302			$\hat{\alpha}$	2.1132552	2.0918893	2.1095845
		$\hat{\theta}$	1.11962212	1.08169871	1.07847996			$\hat{\theta}$	1.090619255	1.08959176	1.06341091
	MSE	$\hat{\omega}$	0.4345895	0.6392675	0.51416972		MSE	$\hat{\omega}$	0.233121709	0.12152551	0.12865889
		$\hat{\delta}$	2.04734115	0.6896355	0.4155742			$\hat{\delta}$	1.6409932	0.4489576	0.4801535
		$\hat{\alpha}$	0.8640154	0.3044784	0.3516827			$\hat{\alpha}$	0.5356266	0.1887299	0.2365791
		$\hat{\theta}$	0.12778147	0.04918305	0.04569176			$\hat{\theta}$	0.072765749	0.04564394	0.04383683
	RMSE	$\hat{\omega}$	0.6592340	0.7995421	0.71705629		RMSE	$\hat{\omega}$	0.482826789	0.34860509	0.35869053
		$\hat{\delta}$	1.43085330	0.8304430	0.6446505			$\hat{\delta}$	1.2810126	0.6700430	0.6929311
		$\hat{\alpha}$	0.9295243	0.5517956	0.5930284			$\hat{\alpha}$	0.7318651	0.4344305	0.4863940
		$\hat{\theta}$	0.35746534	0.22177252	0.21375631			$\hat{\theta}$	0.269751273	0.21364444	0.20937246
	Bias	$\hat{\omega}$	0.1247855	0.2614104	0.05949808		Bias	$\hat{\omega}$	0.003106833	0.03243129	0.01401493
		$\hat{\delta}$	0.07164501	0.1864215	0.2281253			$\hat{\delta}$	0.2193209	0.2066230	0.1143047
		$\hat{\alpha}$	0.4646745	0.1241325	0.2300302			$\hat{\alpha}$	0.2132552	0.1918893	0.2095845
		$\hat{\theta}$	0.01962212	0.01830129	0.02152004			$\hat{\theta}$	0.009380745	0.01040824	0.03658909
140	Mean	$\hat{\omega}$	1.53952724	1.7250935	1.61235302	280	Mean	$\hat{\omega}$	1.61721954	1.64095786	1.57583611
		$\hat{\delta}$	1.4086616	1.1287	1.1367819			$\hat{\delta}$	1.4972093	1.20968389	1.21383508
		$\hat{\alpha}$	2.2042555	2.0975041	2.2004221			$\hat{\alpha}$	2.0856541	2.1042104	2.0366132
		$\hat{\theta}$	1.09014082	1.06284354	1.02318118			$\hat{\theta}$	1.106398438	1.04535746	1.08562392
	MSE	$\hat{\omega}$	0.25843474	0.3274072	0.18176731		MSE	$\hat{\omega}$	0.31906997	0.18466328	0.08248827
		$\hat{\delta}$	1.6269457	0.4979029	0.4210810			$\hat{\delta}$	2.0465212	0.46596600	0.32846800
		$\hat{\alpha}$	0.6301536	0.2780136	0.3535798			$\hat{\alpha}$	0.4463212	0.2124728	0.1252380
		$\hat{\theta}$	0.06320890	0.06203874	0.03729340			$\hat{\theta}$	0.056805371	0.03206397	0.02236085
	RMSE	$\hat{\omega}$	0.50836477	0.5721951	0.42634178		RMSE	$\hat{\omega}$	0.56486279	0.42972466	0.28720771
		$\hat{\delta}$	1.2755178	0.7056224	0.6489075			$\hat{\delta}$	1.4305667	0.68261702	0.57312128
		$\hat{\alpha}$	0.7938221	0.5272699	0.5946258			$\hat{\alpha}$	0.6680727	0.4609478	0.3538898
		$\hat{\theta}$	0.25141380	0.24907578	0.19311498			$\hat{\theta}$	0.238338775	0.17906414	0.14953546
	Bias	$\hat{\omega}$	0.06047276	0.1250935	0.01235302		Bias	$\hat{\omega}$	0.01721954	0.04095786	0.02416389
		$\hat{\delta}$	0.1086616	0.1713000	0.1632181			$\hat{\delta}$	0.1972093	0.09031611	0.08616492
		$\hat{\alpha}$	0.3042555	0.1975041	0.3004221			$\hat{\alpha}$	0.1856541	0.2042104	0.1366132
		$\hat{\theta}$	0.00985918	0.03715646	0.07681882			$\hat{\theta}$	0.006398438	0.05464254	0.01437608

4.2 Ordinary Least Squares - LSE

The equation for this method is given by the form [31], [12]:

$$\varphi(\vartheta) = \sum_{i=1}^{m}\left[F(x_i) - \frac{i}{n+1}\right]^2$$

$$\varphi(\vartheta) = \sum_{i=1}^{n}\left[1 - e^{-\omega\left[-e^{-\alpha x^{-\theta}}.\log\left(1-e^{-\alpha x^{-\theta}}\right)\right]^{\delta}} - \frac{i}{n+1}\right]^2 \quad (32)$$

4.3 Weighted Least Squares - WLS

The equation for this method is given by the form [31], [12]:

$$W(\vartheta) = \sum_{i=1}^{n} W_i\left[F(x_i) - \frac{i}{n+1}\right]^2$$

$$W(\vartheta) = \sum_{i=1}^{n} W_i\left[1 - e^{-\omega\left[-e^{-\alpha x^{-\theta}}.\log\left(1-e^{-\alpha x^{-\theta}}\right)\right]^{\delta}} - \frac{i}{n+1}\right]^2 \quad (33)$$

Equations (31), (32), and (33) are derived for the four parameters $(\omega, \delta, \alpha, \theta)$ and then set equal to zero to obtain an estimate of parameters for the EF model.

5 SIMULATION

Monte Carlo techniques are used to estimate complex distributions through random sampling approaches. The accuracy with which three estimators (MLE, LSE, and WLSE) product parameters EF distribution over sample size $N = 70, 140, 210, 280, \ldots$ up to 100 was evaluated for this work using these techniques. In addition to bias calculations [30], the results were assessed using MSE [31] and the root its RMSE [32]. The samples $N = 70, 140, 210,$ and 280 yielded the most accurate estimates of parameters $\omega, \delta, \alpha,$ and θ for the compared parameters. The sample sizes are shown in Table 4, the simulation was performed using R programming language.

Table 4 indicates that the parameter estimates approach true values as the sample size increasing as the sample size increases. Bias decreases with increasing sample size, especially for MLE, confirming the unbiasedness of this method compared to LSE and WLSE. MLE exhibits superior performance in most cases, especially for parameters δ and α, Where MSE and RMSE values are smaller compared to LSE and WLSE, thus, MLE has the best accuracy and consistency, followed by WLSE and LSE.

6 APPLICATION

To demonstrate the effectiveness of EF distribution in practical applications, it was applied to two data sets. The first set represented medical data, the first dataset corresponds to the remission times of a random sample of 128 bladder cancer patients. The second dataset pertains to engineering reliability data and consists of the failure times of compressive carbon fibers, measured for 69 components each with a length of 50 mm. The descriptive statistics for the two sets of data are shown as follows:

The results of the proposed distribution were compared with six other distributions. Table 5 presents the CDF functions of these comparative distributions, as follows:

Table 5: CDF function for comparative distributions.

Distribution	CDF
Beta Fréchet distribution (BeF)	$\beta\left(e^{-\alpha x^{-\theta}}, \omega, \delta\right)$
Kumaraswamy Fréchet distribution (New) (KuF)	$1 - \left(1 - \left(e^{-\alpha x^{-\theta}}\right)^{\omega}\right)^{\delta}$
Exponential Generalized Exponential Fréchet distribution (New) (EGF)	$\left(1 - \left(e^{-\alpha x^{-\theta}}\right)^{k}\right)^{c}$
Log Gamma Fréchet	$\frac{1 - e^{1-\left(1-\omega e^{-\alpha x^{-\theta}}\right)^{\delta}}}{1 - e^{1-(1-\omega)^{\delta}}}$
[0,1] Truncated Exponentiated Exponential Fréchet (New) ([0,1] TEEF)	$\frac{\left(1 - e^{-\alpha\omega x^{-\theta}}\right)^{\delta}}{(1 - e^{-k})^{c}}$
Fréchet distribution (F)	$e^{-\alpha x^{-\theta}}$

Table 6: Results of the criteria for the distributions.

	Dist.	-L	AIC	CAIC	BIC	HQIC
Data set 1	EF	411.7591	831.5182	831.8461	842.895	836.1405
	BeF	415.4692	838.9383	839.2662	850.3151	843.5605
	KuF	414.0446	836.0892	836.4171	847.466	840.7114
	EGF	435.8316	879.7564	880.0842	891.1331	884.3786
	N[0,1] NHF	413.961	835.9219	836.2498	847.2987	840.5442
	N[0,1] TEEF	415.7867	839.5735	839.9014	850.9502	844.1957
	F	460.964	925.928	926.0248	931.6164	928.2391
Data set 2	EF	34.51252	77.02519	77.69186	85.72274	80.45693
	BeF	38.0213	84.0682	84.73487	92.76575	87.49994
	KuF	36.99326	81.99025	82.65692	90.6878	85.42199
	EGF	37.90646	83.81551	84.48218	92.51306	87.24725
	N[0,1] NHF	40.77596	89.55381	90.22048	98.25136	92.98555
	N[0,1] TEEF	35.51778	79.03631	79.70298	87.73386	82.46806
	F	43.86001	91.72003	91.91358	96.0688	93.4359

Table 7: Results of the criteria for the distributions.

Data	Dist.	W	A	K-S	p-value
Data set 1	EF	0.1287589	0.9580693	0.0769401	0.4397636
	BeF	0.1902141	1.505737	0.08963973	0.259238
	KuF	0.1571864	1.27655	0.07946541	0.3989351
	EGF	0.7006894	4.782829	0.1407645	0.01303947
	N[0,1] NHF	0.1736346	1.304028	0.09233958	0.2289807
	N[0,1] TEEF	0.194154	1.545229	0.08825249	0.2759158
	F	1.404492	8.756085	0.1898896	0.000210589
Data set 2	EF	0.0336067	0.2259957	0.06545795	0.9433906
	BeF	0.1380418	0.8230522	0.09955464	0.5398611
	KuF	0.1104121	0.6573354	0.09323381	0.6243478
	EGF	0.1306284	0.7766481	0.09202611	0.640751
	N[0,1] NHF	0.173459	1.071343	0.1308811	0.2154578
	N[0,1] TEEF	0.0288085	0.2971873	0.04868391	0.9978748
	F	0.275234	1.651979	0.1249851	0.2618771

This comparison uses eight measures. The Good-of-fit: Kolmogorov-Smirnov (KS), Anderson-Darling (A), Cramer-von-Mises (W) and p-value with HQIC, BIC, AIC, and CAIC information criteria [32]. These measures, which are commonly employed to evaluate the goodness of fit of statistical models, are reported in Tables 5 and 6, respectively Table 6 shows EF distribution achieves the lowest values for all metrics in both datasets, indicating a clear advantage in data fitting. EF outperforms all comparable distributions in modeling medical and engineering data, making it the optimal model according to information metrics.

Table 7 presents the results of statistical goodness-of-fit tests. EF achieves the lowest K-S value in both datasets, 0.0769 (dataset 1) and 0.0654 (dataset 2). At the same time, the p-value for EF is high (>0.43 and >0.94), failing to reject the distribution hypothesis (i.e., good fit). EF passes all statistical goodness-of-fit tests with the best performance, supporting its use in modeling survival and material durability data [33].

As a visual evaluation to illustrate the results of Tables 6 and 7, the fitted densities for both types of data are plotted, as well as the empirical CDF for the data, which is shown in the Figures 5-8.

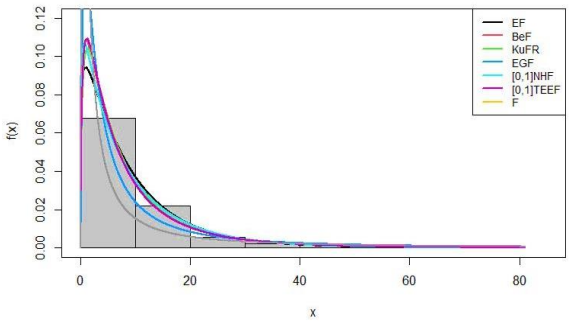


Figure 5: Fitted densities for Data 1.

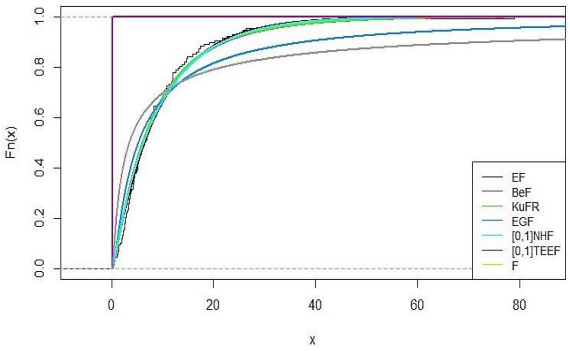


Figure 6: Empirical CDF for Data 1.

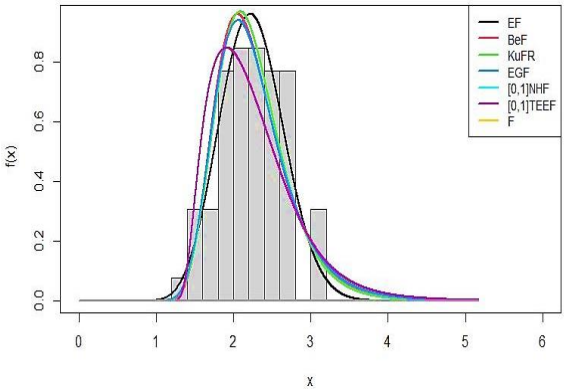


Figure 7: Fitted densities for Data 2.

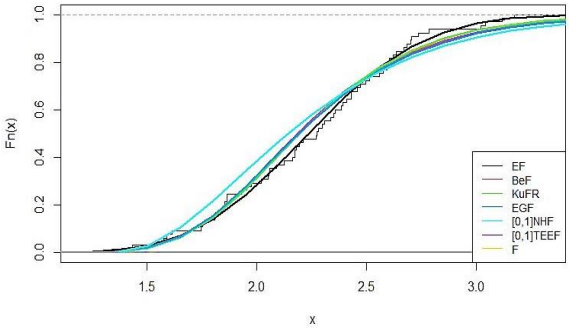


Figure 8: Empirical CDF for Data 2.

Figure 5 shows that the EF curve accurately captures the long tail of the data, reflecting its ability to model extreme values. This is consistent with the heavy-tailed distribution characteristic of EF, as shown in the previous tables. The superiority of EF in this context supports its use in analyzing survival data, where data are often asymmetric and contain extreme values.

Figure 6 shows a high degree of convergence between the two curves, especially in the low and median regions, confirming the goodness of fit of EF to the data. This is consistent with the results of the K-S test, which showed a low value of 0.0769 and a high p-value of 0.439, supporting the hypothesis that the data follow an EF distribution.

Figure 7 shows EF's flexibility in fitting low-variance data concentrated around the median values, as demonstrated by the convergence between the experimental and theoretical curves. This is consistent with the low standard deviation of 0.42 in the engineering data, confirming EF's ability to model engineering data reliability. Figure 8 highlights the accuracy of EF in fitting the empirical CDF, especially in the central range. EF's superior performance here mirrors the results from the previous tables. These results confirm that EF is capable of modeling not only extreme data but also more regular data.

7 CONCLUSIONS

Based on the results obtained in this study, the EF distribution has a high capacity to represent data with heavy tails and positive skewness (it was also confirmed to have high skewness and kurtosis values), and numerical results of the statistical measures. This trait makes it suitable for modeling data with extreme values without changing the underlying data structure, making it applicable in scenarios such as medical survival and engineering reliability. The numerical results proved that the maximum likelihood method was the most accurate and stable for modeling the distribution parameters of the data, with the lowest bias and MSE values compared with the least squares and weighted methods, whose model performance showed a significant improvement with increasing sample size. This type of behavior is consistent with the accuracy of the estimation even on small and medium-sized samples. In applications, EF's distribution was obviously better than the available (competing) distributions on information criteria and fit tests, with the lowest criteria values and the highest statistical significance values. The graphical findings further confirmed these findings by displaying a good agreement between the conceptual model and the practical data and that EF is a faithful and flexible approximation of the real-life data.

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Diabetes Prevalence Forecasting Using GARCH and Deep Learning Models

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Keywords: Type 1 Diabetes, GARCH, LSTM, Time Series, Forecasting, Statistical Stability.

Abstract: The aim of this study is to use cutting-edge statistical and artificial intelligence techniques to assess and forecast the prevalence of type 1 diabetes in Iraqi children. In order to determine the prospective ultimate caseload and the fictitious inflection point, the research used the generalised autoregressive conditional variance (GARCH(p,q)) model to estimate the temporal behaviour of the data. The models under test were subjected to statistical stability conditions, and the AIC and BIC information criteria were used to assess their performance. The findings indicated that, out of all the nonparametric models examined, the GARCH(1,0) model performed the best. However, the paper showed that there were no significant variance fluctuations in the incidence data, which restricts the use of strictly nonparametric models. Deep LSTMNs neural networks were used for time series analysis in order to get around this. Using the ideal parameters for the number of layers and iterations, the data was divided into an 80% training set and a 20% test set. In comparison to other models, the LSTMNs findings showed the lowest mean squared errors, indicating a good capacity to predict future values. This implies that an efficient method for tracking upcoming changes in chronic illnesses is to combine deep learning algorithms with traditional statistical models. To enhance planning and response to the epidemic load of chronic illnesses, the paper suggests using this strategy in medical modelling and health forecasting.

1 INTRODUCTION

One of the most common chronic metabolic diseases affecting kids and teenagers is type 1 diabetes. Chronically high blood glucose levels are the result of the autoimmune death of the beta cells in the pancreas that secrete insulin [1]. The condition is severe because it directly affects the body's metabolic equilibrium, affecting numerous essential processes such as protein, lipid, and glucose metabolism, as well as oxidative stress and inflammatory pathways [2].

Laboratory indicators like fasting glucose, glycated hemoglobin (HbA1c), insulin levels, C-peptide, and inflammatory markers like CRP, triglycerides, and cholesterol are crucial for comprehending the course of a disease and evaluating the efficacy of treatment [3].

Long-term tracking of these markers yields precise data on the physiological and metabolic alterations linked to the illness and aids in the prediction of further consequences, including microvascular and macrovascular disease [1], [2].

Advances in artificial intelligence and statistical analysis techniques have made it possible to use deep neural networks like long-short-term memory networks (LSTMNs), a type of recursive neural network designed to handle time-series data and address the vanishing gradient problem [4], as well as time series models like the generalized autoregressive conditional variance (GARCH) model, which was developed as an extension of the Autoregressive Conditional Heteroskedasticity (ARCH) model proposed by Robert F. Engle in the 1980s [5].

More opportunities for early intervention and better treatment plans are made possible by the development of predictive models that can recognize pivotal moments in the disease trajectory and forecast future biochemical markers thanks to the combination of statistical analysis and artificial intelligence [6].

The purpose of this paper is to forecast future trends and possible changes in biomarkers by analyzing biochemical data from pediatric type 1 diabetes patients in Iraq using a combination of GARCH models and LSTMNs approaches. In order to better understand disease dynamics and enhance healthcare practices, we want to offer a scientific framework that integrates biochemistry and sophisticated statistical analysis.

2 LITERATURE REVIEW

Over the last several decades, time series analysis has developed into a vital tool for researching health issues, especially long-term conditions like diabetes. In order to solve the issue of non-stationary variance in economic data, Engle proposed the ARCH model in 1982, making it one of the first statistical models in this area. It uses the squares of the previous mistakes to depict the conditional variance as a series [7].

The generalized ARCH model (GARCH), which Bollerslev expanded in 1986, is more adaptable when dealing with very volatile data because it combines ARCH components with other components to better correctly describe the conditional variance [5].

Subsequent iterations of this model, including TARCH [8], GJR-GARCH [9], and EGARCH [10], attempted to address certain facets of variance, including the leverage impact and volatility asymmetry. GARCH models have been used in the healthcare industry to analyze data on infectious and non-infectious disorders. For example, [11] used GARCH to Middle Eastern diabetes data and showed that it was successful in describing the disease's temporal patterns.

The analysis of temporal data has been transformed by artificial intelligence in tandem with classical statistical models. This is especially true since the development of LSTMNs by [12], which has demonstrated their effectiveness in processing serial data with long-term temporal correlations [4].

As demonstrated by a study by [13], which compared the effectiveness of LSTMs with conventional statistical models in predicting the prevalence of diabetes and discovered that LSTMNs outperformed them in accuracy and capacity to identify intricate patterns in data, LSTMNss have been widely used in the prediction of chronic diseases.

This research demonstrate that integrating contemporary deep learning methods like LSTMNs with statistical models like GARCH offers an integrated framework for evaluating medical time series, improving prediction accuracy, and assisting with data-driven health planning choices.

2.1 ARCH Model

ARCH statistical model is used to examine time series volatility and forecast future volatility. The ARCH model is used in finance to assess risk by offering a volatility framework that accurately reflects actual market conditions. Higher volatility follows times of high volatility, while lower volatility follows periods of low volatility, according to ARCH modeling [14], ARCH model, which will have the formula [15]:

$$y_t = \sigma_t \epsilon_t \text{ where } \epsilon_t \sim iid\ N(0,1)$$

$$\sigma_t^2 = \omega + \sum_{j=1}^{Q} \varphi_j\, y_{t-j}^2 \qquad (1)$$

Where σ_t^2 is the conditional variance, and $\omega, \sum_{j=1}^{Q} \varphi_j$ are the parameters of the model.

This model is predicated on the martingale difference [15],

$$E(Y_{t+1}^2 / F_t) = \sigma_t^2 \qquad (2)$$

Where F_t is a $\sigma - field$ of a random variables called a sometimes filter $(y_{t-1}, y_{t-2}, \dots, y_{t-Q})$ [8].

The large-scale conditional autoheteroscedasticity (GARCH(Q, P)) model was introduced by Bollerslev in 1986 as an extension of the ARCH model, aiming to address limitations related to time-varying conditional variance and provide a more flexible model for predicting time series volatility. This model is defined by the following system of equations [15]:

$$y_t = \sigma_t \epsilon_t \text{ where } \epsilon_t \sim iid\ N(0,1)$$

$$\sigma_t^2 = \omega + \sum_{j=1}^{Q} \varphi_j\, y_{t-j}^2 + \sum_{i=1}^{P} \gamma_i\, \sigma_{t-i}^2 \qquad (2)$$

Where ω is a constant and φ_j, γ_i a represent the ARCH and GARCH model parameters, respectively.

By imposing certain restrictions on the coefficients of the conditional variance equation, the value of ω must be > 0, to ensure that the variance remains positive and that negative values cannot occur, which maintains the mathematical consistency and validity of the statistical model, $\varphi_j \geq 0\ \forall j,\ j = 1,2, \dots, Q$، $\gamma_i \geq 0\ \forall i, i = 1,2, \dots, P$, a

$\sum_{j=1}^{Q} \varphi_j + \sum_{i=1}^{P} \gamma_i < 1$ then the conditional variance is:

$$\sigma_t^2 = \frac{\omega}{1 - (\sum_{j=1}^{Q} \varphi_j + \sum_{i=1}^{P} \gamma_i)} \quad (3)$$

Despite the merits of GARCH models, they exhibit shortcomings, as noted by Black in 1976, namely the inability to capture the Leverage effect [16].

For a GARCH model to maintain stationarity, the conditional variance must converge to the unconditional variance over time, so that the mathematical condition $\sigma_t \rightarrow \sigma_y$ at infinity is met, ensuring that the variance remains constant and does not deviate toward unstable values [17], [18].

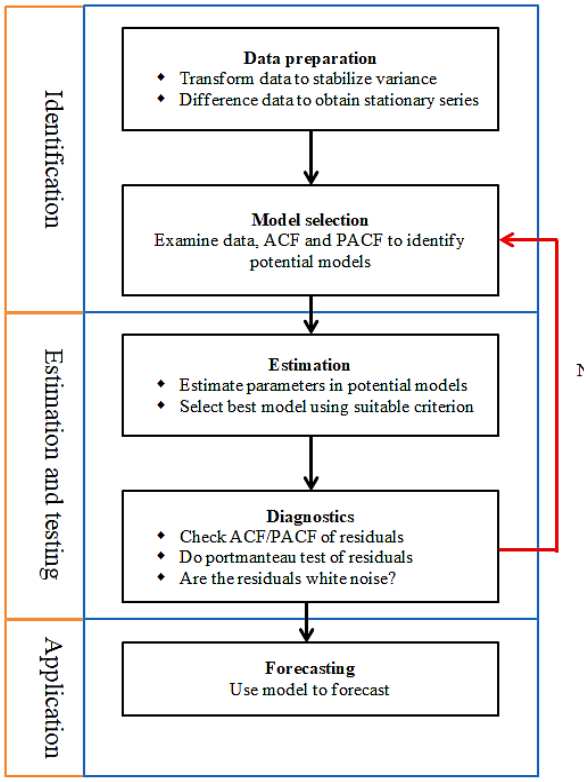


Figure 1: Box-Jenkins flow chart [19].

2.2 Box-Jenkins Method

Box and Jenkins developed this method in 1970 and subsequently underwent further developments between 1970 and 1996 to include a range of complementary techniques as needed. This methodology aims to achieve optimal predictive accuracy through three main stages [15]:

1) Identification. This includes data preparation and selecting the appropriate model for the time series under study.
2) Estimation and Testing. This involves estimating model parameters and performing diagnostics to ensure its suitability and validity for prediction.
3) Application. This is where the developed model is used to make the required predictions and make decisions based on them.

Figure 1 illustrates the various stages of this methodology graphically, making it easier to understand the sequence of processes and steps involved.

2.3 Model Order Selection Criteria

2.3.1 Akaike Information Criterion (AIC)

This model is considered the most widely used in statistical literature, and is represented by the following mathematical function [20]:

$$AIC(p,q) = -2\,log(maximum\ likelehood) + 2k \quad (5)$$

Where k is number of parameters in proposed model.

2.3.2 Bayesian Information Criterion (BIC)

This criteria was introduced similarly to the Akaike criterion to get enhanced convergence features and is expressed by the following function [18], [21]:

$$BIC = -2l(maximum\ likelehood) + k\,ln\,n \quad (6)$$

Where m represents the number of observations or measurements used in the analysis.

2.3.3 Long Short-Term Memory Networks (LSTMNs)

LSTMNs are effective tools for classifying, processing, and predicting time series data, especially when these series contain unspecified time intervals between important events [12].

These networks were developed to address the problem of vanishing gradients that hinders the learning of traditional neural networks. LSTMNs belong to the class of artificial neural networks (ANNs) used in the fields of artificial intelligence. Recurrent neural networks (RNNs) are characterized by their ability to process both individual data points and entire data series [13].

3 ANALYSIS AND RESULTS

3.1 Collection of Data

This study is based on 571 observations of approved diabetes cases, recorded between January 1, 2021, and July 25, 2022, taken from the Iraqi Ministry of Health official website. To achieve optimal predictive accuracy, the GARCH model's stability criteria will be applied to this data. This ensures that the model's conditional variance converges with its unconditional variance, thus achieving model stability and reliable future predictions based on time series data.

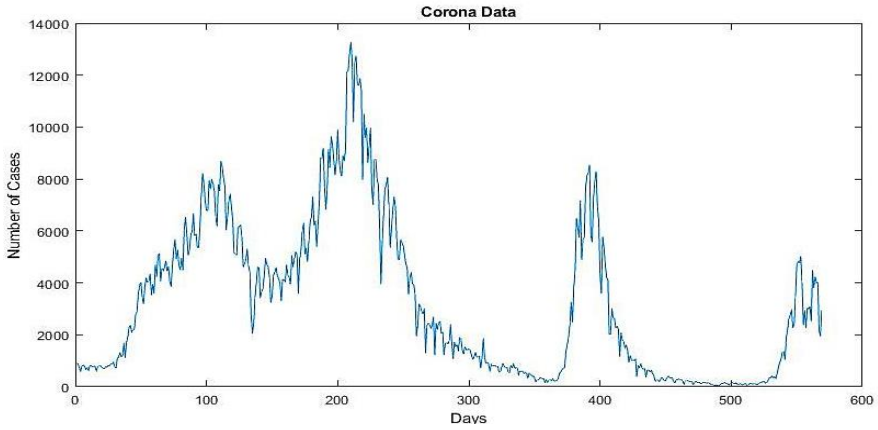
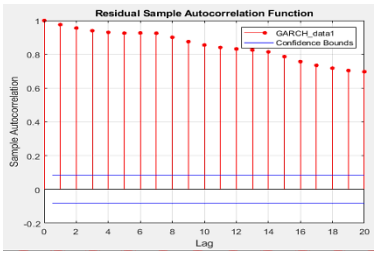
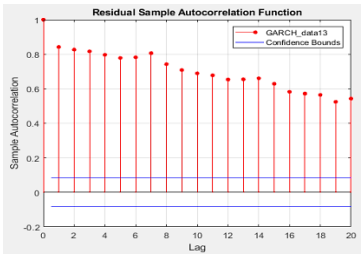


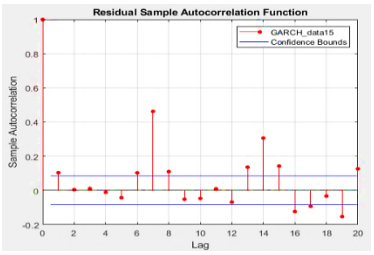
Figure 2: Historical statistics about diabetes from January 1, 2021, to July 25, 2022.



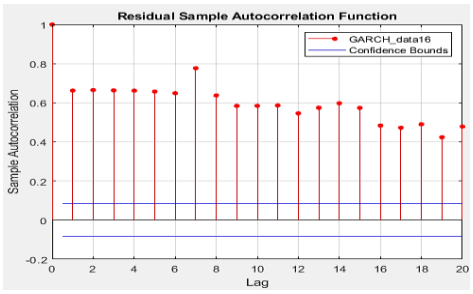
GARCH(0,0)



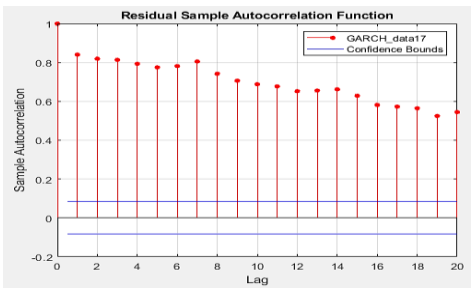
GARCH(1,1)



GARCH(1,2)

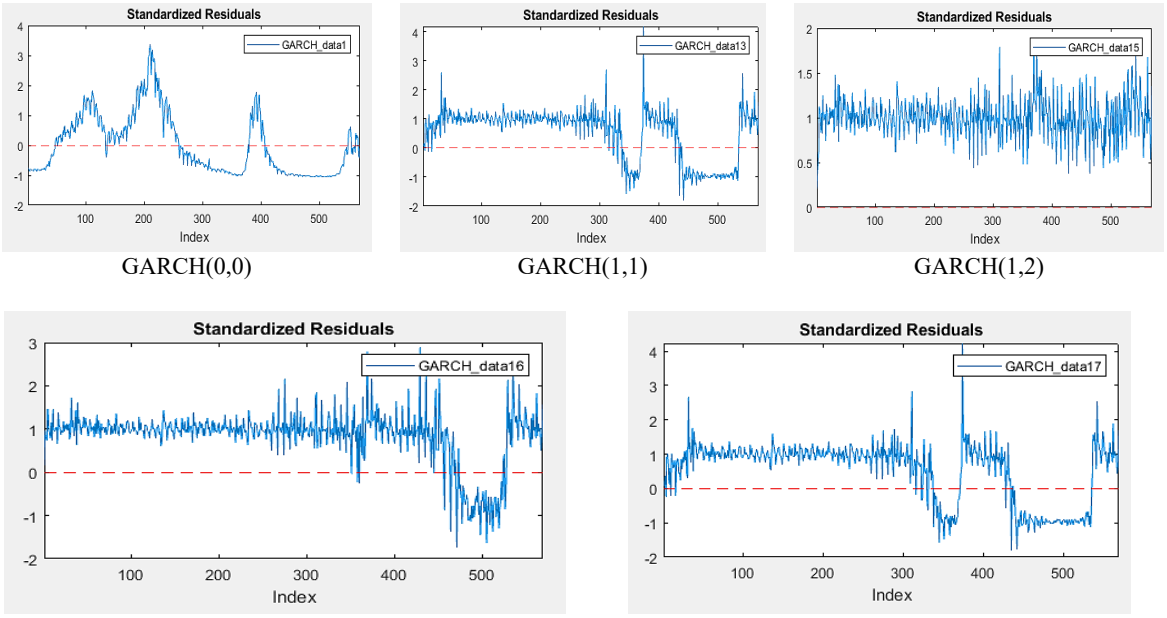


GARCH(0,1)



GARCH(0,2)

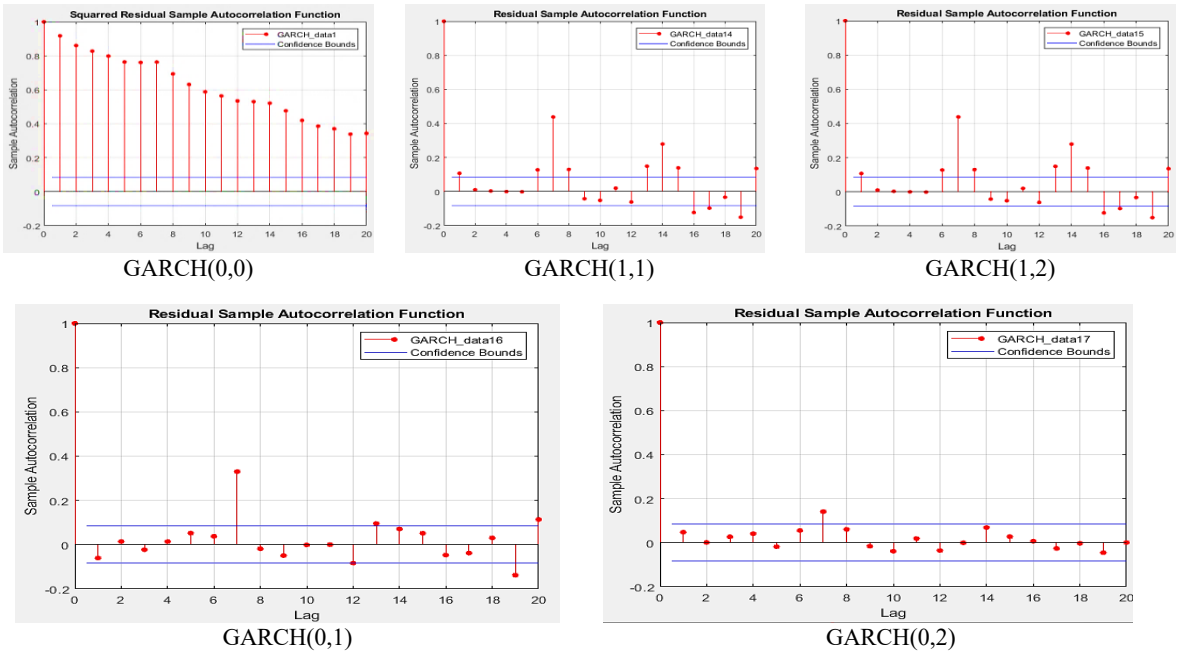
Figure 3: Autocorrelation functions with varying orders.



GARCH(0,0) GARCH(1,1) GARCH(1,2)

GARCH(0,1) GARCH(0,2)

Figure 4: Residual functions with varying orders.



GARCH(0,0) GARCH(1,1) GARCH(1,2)

GARCH(0,1) GARCH(0,2)

Figure 5: Autocorrelation functions of the GARCH model after Residual functions with different orders.

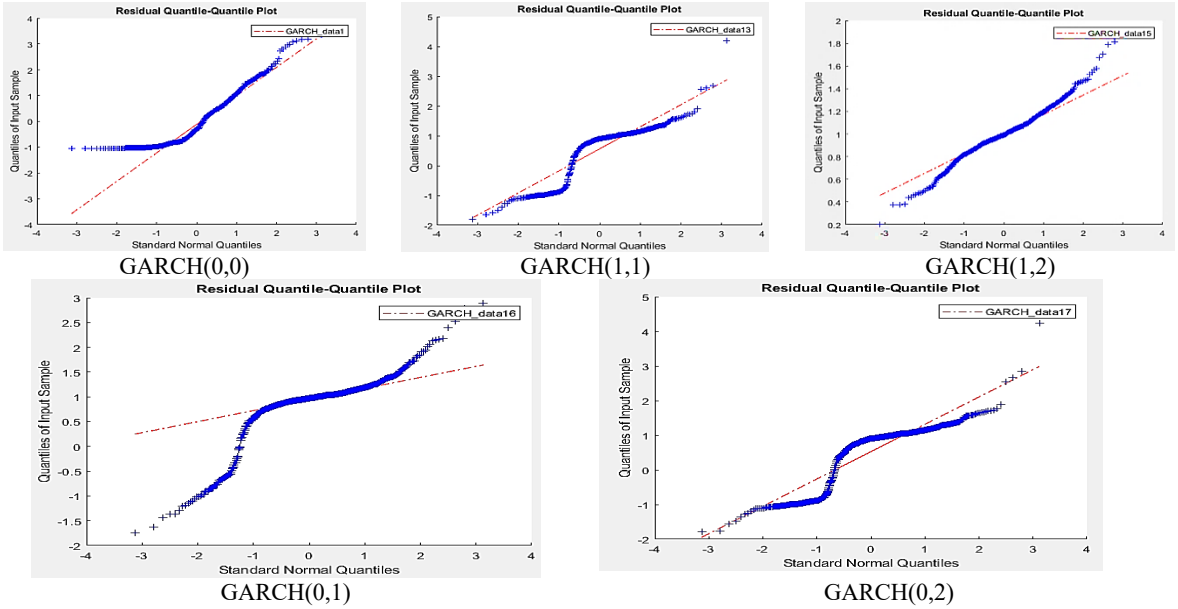


Figure 6: The QQ Plot functions with varying orders.

Table 1: The parameter values of models of varying rank derived from the GARCH model.

GARCH(P,Q)	Constant	ARCH(1)	ARCH(2)	GARCH(1)	GARCH(2)
GARCH(0,0)	$8.99e+06$	0	0	0	0
GARCH(1,1)	$1.708e+04$	0.829	0	0.171	0
GARCH(1,2)	$2.176e+04$	0.796	0.204	0	0
GARCH(0,1)	$3.049e+03$	1.000	0	0	0
GARCH(0,2)	$2.176e+04$	0.796	0.204	0	0

Table 2: The AIC and BIC values of various ranks from the GARCH model.

GARCH(P,Q)	AIC	BIC
GARCH(0,0)	1.073e+04	1.739e+04
GARCH(1,1)	9.899e+03	9.917e+03
GARCH(1,2)	1.009e+04	1.010e+04
GARCH(0,1)	9.848e+03	9.861e+03
GARCH(0,2)	9.898e+03	9.915e+03

3.2 Modeling and Analyzing of Data by GARCH Model

The GARCH model will be applied to the data, observing and confirming that the conditional variance converges to the unconditional variance, which is a prerequisite for ensuring model stability and reliable predictions. The process involves several sequential steps, beginning with identifying changes in the data, then building the model according to appropriate statistical criteria. This is followed by estimating the model parameters using appropriate estimation methods, then assessing the model's suitability through diagnostic tests, and finally forecasting the future conditional variance. Matlab R2020a was used to create and program the time series data, evaluating several models of different orders to find the optimal model that best fits the data.

The data visualization phase is the first and important step in time series analysis, helping to understand the data pattern and identify any potential trends or fluctuations. Figure 2 shows a time series graph displaying historical data on the number of diabetes cases from January 1, 2021, to July 25, 2022.

The next step involves converting the original series into a series of returns to facilitate volatility

analysis, and then converting these returns into a series of squared errors for conditional variance analysis. Autocorrelation functions (ACFs) for the GARCH model were also calculated and displayed at different levels. Figure 3 illustrates the ACFs for a set of models, which helps assess the correlation structure in the data and select the most appropriate model.

After completing this step, we transform the squared error series into a series of residuals by performing the Young-Box test to assess the effect of heteroscedasticity over multiple lags. Figure 4 shows several residual functions for a GARCH model across multiple orders, while Figure 5 displays the autocorrelation functions for these models.

We will now examine the quantile-quantile plot, or QQ Plot, which visually evaluates whether the remaining series adheres to a normal distribution, as seen in Figure 6.

In addition to the graphs presented previously, which illustrate the general trend of the series, the model's suitability for future predictions must be evaluated. Tables 1 and 2 will be presented: the first shows the estimated parameters for each of the proposed models, and the second shows the results of the AIC and BIC values of various ranks from the GARCH model for selecting the optimal model.

A multitude of coefficients with zero values indicates that some model components do not significantly contribute to variance explanation. The conditional variance remains almost constant throughout time, exhibiting little fluctuations, as shown by the GARCH(0,1) model's constant of 1.000. The inadequate time-dependent effect of data variance is shown by the relatively small ARCH and GARCH coefficients in the other models.The GARCH(0,1) model exhibited the optimal fit among the analyzed models, shown by the lowest AIC and BIC values. Despite minor differences in AIC and BIC, GARCH(0,1) is statistically superior than GARCH(1,1). Extremely high GARCH(0,0) scores indicate a suboptimal overall fit to the data.

Thus, the conditional variance of the examined models is shown in Figure 7.

Upon reviewing the preceding stages of data analysis illustrated in graphs and tables, it is evident that the most reliable model for forecasting is the GARCH(1,0) model. However, we must now verify the stability of the selected model by applying its stability conditions and assessing the conditional variance as delineated in (4).

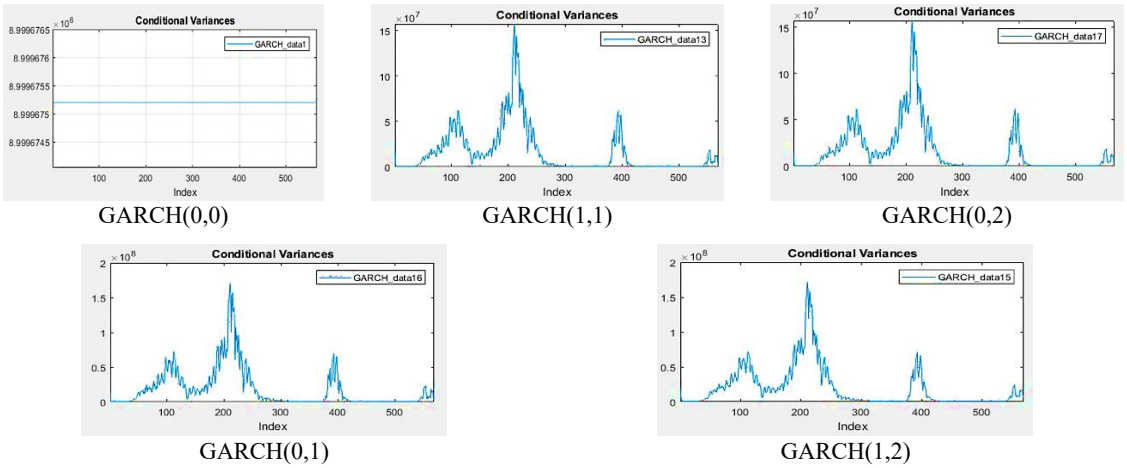
$$\varphi_1 = 1.000$$

After applying stability conditions to the GARCH model, it was confirmed that the model achieves the required stability, which is essential for ensuring the reliability and accuracy of future predictions. This property ensures that the model's conditional variance does not deviate toward unstable values over time but rather converges toward the unconditional variance. The value of the model's unconditional variance is defined as follows:

$$\sigma^2 = \frac{\omega}{1-(\varphi_1+\sum_{i=1}^{2}\gamma_i)} = \frac{3.049e{+}03}{1-1} = \text{unknown value}$$

Therefore, the equation for the GARCH(1,0) model, which is used to predict unconditional variance values, is as follows:

$$y_t = \sigma_t \epsilon_t \text{ where } \epsilon_t \sim iid\ N(0,1)$$
$$\sigma_t^2 = \omega + \varphi_1 y_{t-1}^2 \qquad (7)$$



GARCH(0,0) GARCH(1,1) GARCH(0,2)

GARCH(0,1) GARCH(1,2)

Figure 7: The conditional variance of the GARCH model with varying orders.

3.3 Modeling and Creating by Using LSTM

LSTM, another method for modeling and analyzing time series, will be used in this paper.

The data is segmented into two groups: the training group, including 80% of the observations, and the test group, comprising 20% of the data. Given that the maximum number of hidden layers is 50 and the input consists of a single variable with one lag, after conducting 250 iterations, the minimal mean squared error was 0.0359.

Figure 8 represents the values of the training set, and the Figure 9 illustrates the predicted values of the test set.

And that the value:

$$AIC = 1.1915e + 03$$
$$BIC = 1.1956e + 03$$

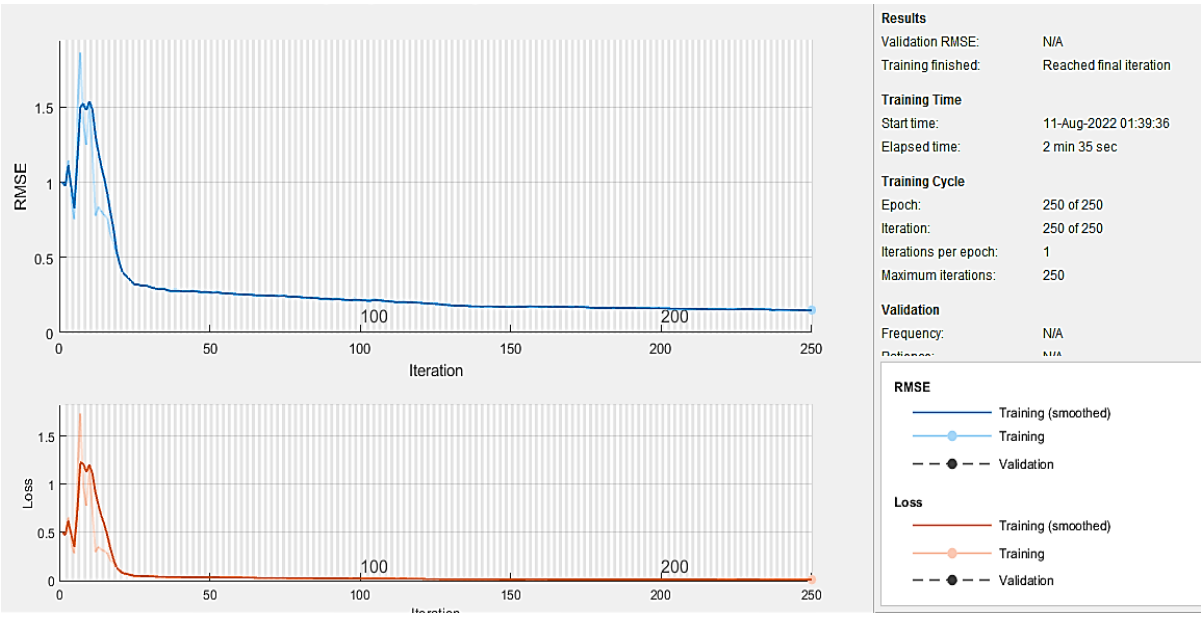


Figure 8: Training progress by using LSTM.

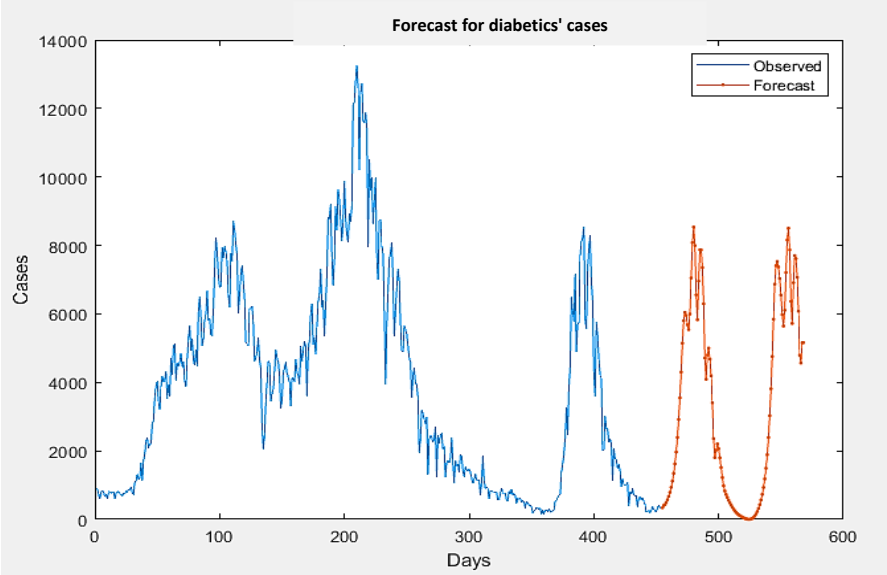


Figure 9: Predicted values for the test set by using LSTM.

Table 3: The estimated values for the training set by using LSTM.

Month	1st week	2nd week	3rd week	4th week
1st month	1.0e+04	0.0638	0.0864	0.0868
2nd month	0.0928	0.1093	0.1113	0.1097
3rd month	0.0645	0.0697	0.0827	0.0876
4th month	0.0556	0.0717	0.0855	0.0891
5th month	0.0770	0.0906	0.0990	0.1114
6th month	0.1142	0.1520	0.1662	0.1869
7th month	0.2191	0.2413	0.2816	0.3214
8th month	0.3410	0.3272	0.3688	0.4079
9th month	0.3670	0.3366	0.3994	0.4174
10th month	0.4275	0.3911	0.4518	0.4843
11th month	0.4218	0.4151	0.4489	0.5073
12th month	0.4666	0.4646	0.5137	0.5586
13th month	0.5359	0.4910	0.5548	0.6284
14th month	0.5397	0.5496	0.6273	0.7160
15th month	0.6388	0.6654	0.7732	0.8326
16th month	0.7046	0.6857	0.7511	0.8121
17th month	0.7513	0.6125	0.6797	0.7346
18th month	0.5528	0.4739	0.5544	0.5809
19th month	0.4740	0.4244	0.4997	0.5175

The numbers are the LSTM model's expected estimations for the training set. From around month 1 to month 15, there is a noticeable increasing trend that suggests a slow rise in the anticipated number of infections. The numbers start to vary and progressively decrease after month 16, demonstrating the model's capacity to identify shifts in trends (Table 3). There is little variation across weeks within a month, which is in line with the overall conclusion that the data is not very volatile.

4 CONCLUSIONS

Since there were few large variance swings in the daily data on confirmed children diabetes cases in Iraq from January 1, 2021, to July 25, 2022, using conventional GARCH models was less successful.

When statistical models were compared, GARCH(0,1) was determined to be the best model in terms of AIC and BIC. However, the data's low conditional variance makes it less reliable for making predictions in the future.

After using GARCH models, certain correlations were still present in the data, according to graphical analysis of residuals and autocorrelation functions (ACFs). This suggests that the models were not able to fully capture the temporal patterns in the series.

Quantile-Quantile (QQ) plots demonstrated that the GARCH models' residuals do not have a perfectly normal distribution, which has an impact on prediction accuracy. With a low mean square error (MSE) of 0.0359 and projected values that were very near to the actual values in the test data, the LSTM network's findings showed a definite advantage over GARCH models in terms of prediction accuracy.

In this instance, LSTM is the best model for short-term forecasts of future pediatric diabetes cases due to its capacity to adjust to temporal patterns, even in the absence of abrupt swings.

Instead of restricting the use of GARCH models to data with significant volatility, the research suggests using AI-based models, such LSTM, to analyze health time series with relative stability of variance.

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Design and Performance Evaluation of an Enhanced Solar Thermal Collector

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Keywords: Solar Energy, Solar Collector, Global Warming, Solar Heater, Structure.

Abstract: This research aims to design and analyze a Scccs2 solar collector with a convex front surface and a corrugated absorber surface that reflects the incident solar radiation via mirrors. The design features a convex front surface that increases the angle of solar radiation capture, while a wavy and convex absorber surface increases the surface area exposed to the sun. In addition, reflective mirrors are used to direct solar radiation to copper tubes mounted above the absorber surface, increasing the efficiency of the Scccs2 solar collector. The new geometry significantly increases the efficiency of the Scccs2 solar collector in converting solar energy into thermal energy.The testing also demonstrates the effect of adding the absorber surface and tubes in a wavy - convex shape on the performance of the Scccs2 collector. To increase the collector's ability to retain thermal energy, two tanks (B1-B2) are installed inside the collector. Scccs2 records (Tout= (65-95) °C, B2= (45-85) °C) for the period from November 2024 to June 2025. The Scccs2 model is capable of operating in partly and completely cloudy weather. In partly cloudy weather, Scccs2 records (Tout= 70°C, B2= 50°C). In completely cloudy weather, it records (Tout= 49°C, B2= 32°C).

1 INTRODUCTION

In recent years, the globe has turned to the study of solar energy as an alternative energy source, turning sun rays into heat. Solar energy is clean, does not harm the environment, and can be utilized indoors. Scientists and researchers must use this energy to develop models and technologies.

In the Middle East, the sun's rays are strong where the Arab country is located between the equator and latitude (37), and between longitude (17) west longitude of Greenwich (60) east of Greenwich, hence the need for energy has grown [1].

Solar energy is one of the most significant types of renewable energy since it uses the sun's radiation to carry heat and light sources; this energy form may be used in a variety of applications [2]-[6].

Solar energy may be utilized for water heating; a solar heater can use sun irradiation to generate hot water [6], [7].to make a substantial contribution to ecologically friendly energy sources, solar-poared heaters must finally demonstrate a positive energy balance throughout the duration of their lives. The industry may lessen its environmental effect and ensure that clean energy production coexists happily with environmental protection by including ecological considerations into the design of solar heaters [8], [9]. Solar water heaters are utilized as auxiliary systems to decrease the consumption of conventional fuel by preheating water in industrial and home sectors [10].

2 EXPERIMENTAL WORK

2.1 Solar Collector Design and Materials Used

All industrial components are inspected and tested, and the new engineering prototype of the Scccs2 solar water heater is put into operation after being exposed to direct solar radiation.

Scccs2 Fabrication Process; The following tools and materials are used to build the new Scccs2 design:

Copper pipe (a diameter of 0.0095cm and a length of 12m), A plastic hose, valves to control the

speed of water flow and matt black paint, Mercury thermometer, electronic thermometer and Graduated glassware, 2 galvanized iron cylindrical tanks with a capacity of 3L (diameter 0.098m, height 0.4m, and thickness 0.003m), Iron plate rolled into a convex sine wave shape (length 1.55m, width 0.6m, thickness 0.002m) for manufacturing the absorber surface of Scccs2, Transparent glass panels (2 pieces (length 0.64m, width 0.24m, thickness 0.003m) & 2 pieces (length 0.64m, width 0.415m, thickness 0.003m)), Reflecting mirrors (length 0.1m, width 0.04m, thickness 0.002m) are fixed on the absorber plate to reflect solar radiation towards copper tubes (a diameter of 0.0095 cm and a length of 12 m) fixed 5 cm above the mirrors, Aluminum clips [11]. (length 0.05 m) to fix the copper tube on the absorber plate and Iron plate for the construction of the Scccs2 structure:

1) Two side panels (length 0.6 m, width 0.25 m, thickness 0.002 m), One rear deck (length 1.15m, width 0.6m, thickness 0.002m) and two side ribs (length 0.25m, thickness 0.002m).
2) Two roof and base panels (Straight rear rib (length 1.15m, thickness 0.002m) & convex front rib (length 1.12 m, thickness 0.002m)).

2.2 Solar Collector Scccs2 Manufacturing

Iron sheets with a thickness of 0.002m and different areas are used to fabricate the Scccs2 structure. The structure is in the shape of a parallelogram, as shown in Figure 1. The front surface of the collector is designed as a convex shape. The convex-wavy absorption surface is fixed inside the collector structure on the convex side, 0.09 m from the convex edge. The absorption surface of the solar collector is an iron sheet (1.55m long, 0.6m wide and 0.002m thick). Reflective mirrors are fixed on it. A copper tube (0.0095 m in diameter and 12 m long) is fixed in a Z-shaped path [1], [12] above the absorption surface (at a distance of 0.05m) using aluminum brackets. Therefore, the path of the copper tube is similar to the path of the absorption plate (wavy-convex) to match the new geometric design of the collector. To increase the absorption of solar radiation and raise the efficiency of the collector, the copper tube, Two tanks (B1, B2), and the visible parts of the absorption plate are painted in matte black, as shown in Figure 1.

In Figure 2, An air chamber is added behind the absorber to act as a thermal insulator, preventing thermal energy loss from the rear surface of the collector and helping to conserve the heat gained. The Scccs2 is manufactured using steel sheets. The dimensions of the collector's side panels are (0.6 m long, 0.25 m wide and 0.002 m thick). The dimensions of the rear deck panel are (1.15 m long, 0.6 m wide and 0.002 m thick). As for the collector roof and base, the straight rear side is 1.15 m long, and the convex front side is 1.12 m long. The center of convexity is 0.5 m from the center of the rear side. The two side sides are 0.25 m long, from the rear side to the ends of the convex side. Lead-brazing and electric welding is used to assemble the Scccs2 body parts in local fabrication workshops.



Figure 1: The manufacturing steps of Scccs2, and the installation location of the absorber plate and copper tube.

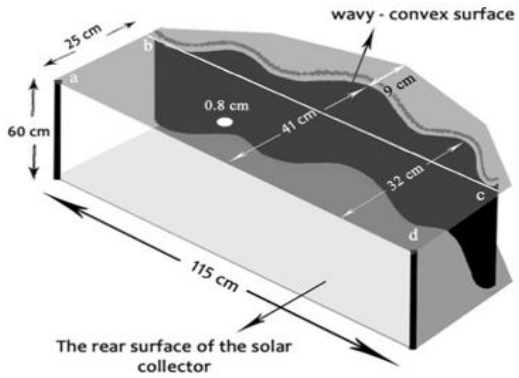


Figure 2: The structure of the collector, the absorption surface, and the buffer chamber.

2.3 The Insulating Room

The engineering design of the Scccs2 collector includes an air room between the absorber surface and the back of the collector. This room is tightly sealed to take advantage of the global warming

phenomenon effect. The benefit of this chamber is that it prevents the loss of thermal energy from the back of the collector (due to the global warming effect and thermal balance within the room), instead of using expensive and environmentally harmful thermal insulators when they deteriorate. Figure 3 shows the dimensions of this room and the location of the absorber surface.

2.4 Convex Front Surface and Absorption Surface (Wavy-Convex) to Scccs2

In the new Scccs2 engineering model, the front surface is designed in a convex shape to increase the solar radiation capture angle and align with the horizontal movement of the sun. This eliminates the need to rotate the Scccs2 solar collector to be perpendicular to the sun, as it is demonstrated in this research. To increase the absorbing surface area, it is designed in a wavy, convex shape. Reflective mirrors (0.1 m long, 0.04 m wide and 0.002 m thick) are installed on the absorbing surface to reflect the incident solar radiation toward the copper pipe. This increases the amount of thermal energy inside the collector, thus increasing the water temperature. The copper pipe (diameter 0.0095m, length 12m) is installed 0.05 m above the absorbing surface and adopted the wave-like shape of the absorbing surface. Figure 3, shows the stages of manufacturing the absorber surface (length 1.55 m, width 0.6 m, thickness 0.002 m). Using a metal bending machine, the absorber surface resembles a sine wave, with three peaks and four concave surfaces.

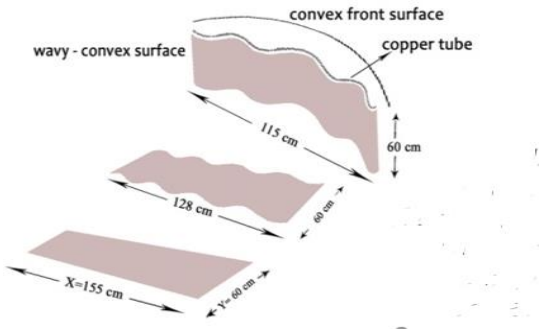


Figure 3: Schematic diagram of the measurements and manufacturing stages of the absorbent surface.

The Scccs2 solar collector's engineering design is capable of capturing and retaining thermal energy (Fig. 4), raising the temperature of the water passing through the copper tube and tanks (B1, B2). Two tanks (B1, B2) (3L capacity, 0.098m diameter, 0.04m height, and 0.002m wall thickness) are installed inside Scccs2 on the edges of the absorbent surface. B1 receives the external tank water; while B2 collects the usage water coming from the collector.

To take advantage of the global warming effect, a transparent glass cover (thickness of 0.003m) is placed on the convex front surface of the Scccs2, making the solar collector as shown in Figure 5.



Figure 4: Shows the locations of valves V1, V2, and V3 in Scccs2.



Figure 5: The finish shape of the Scccs2.

In Basra; in summer, the solar collector is perpendicular to the sun at 15° with the horizon, and 45° in winter [1], [11] - [13]. The Scccs2 does not need to be rotated horizontally to be perpendicular to the sun, due to the convex of the front surface and the convex and waviness of the absorber surface; this is one of the advantages of this model.

Measuring Instruments; Mercury and Electronic Thermometer & AWOS Solar Radiation Meter.

- Use a mercury thermometer to calibrate an electronic thermometer and measure temperatures.
- The electronic thermometer is locally manufactured to accurately measure temperature and humidity. It can measure

more than one temperature simultaneously, saving time and effort.

- An automatic weather station (AWOS) at Basra International Airport measures atmospheric elements, including solar radiation.

3 RESULTS AND DISCUSSION

3.1 Solar Collector Efficiency in Different Weather Conditions

The Scccs2 solar collector is tested under different weather conditions using two testing methods to determine the efficiency of the collector's engineering design.

Vertically; the collector's angle of inclination relative to the horizon is fixed in summer or winter, then the collector is rotated horizontally to be perpendicular to the sun every hour during daytime operation. The other method is to stabilizing the collector horizontally in the direction it faces the sun at 11:00 a.m.

The collector Scccs2 is supplied with water via valve V1, which passes through tank B1. The water then passes through a copper pipe, reaching the end of the pipe. The copper pipe branches into two branches: The first branch connects to valve V2 to record the water temperature (Tout). The second branch connects to tank B2, which is the water collection tank (Ttank), and then the water comes out from B2 through valve V3 to record the water temperature (Ttank). After testing the Scccs2 during daylight hours (from 9:00 a.m. to 2:00 p.m. for the months of November 2024 to June 2025), the results are recorded under various weather conditions, using the two previous examination methods, the results are as shown in Table 1 And Figures 6 and 7.

Table 1: The results are recorded by Scccs2 under different weather conditions.

Weather	Rotate Scccs2 towards the sun			Stability Scccs2 towards the sun		
	Date	T_{out}	T_{tank}	Date	T_{out}	T_{tank}
Sunny	04/06/2025	97	84	05/06/2025	97	83
Partly cloudy	23/12/2024	70	50	22/12/2024	70	50
Overcast	24/12/2024	49	32	25/12/2024	47	31

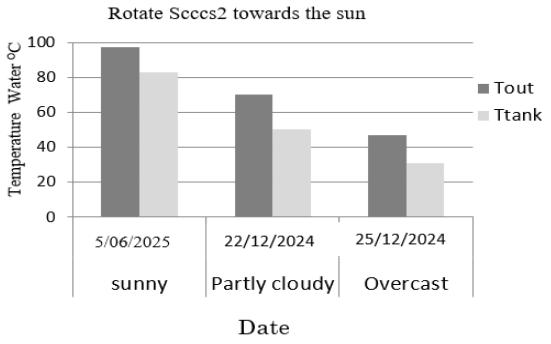


Figure 6: A graph showing the results recorded by Scccs2 under different atmospheric conditions when the collector is moved towards the sun.

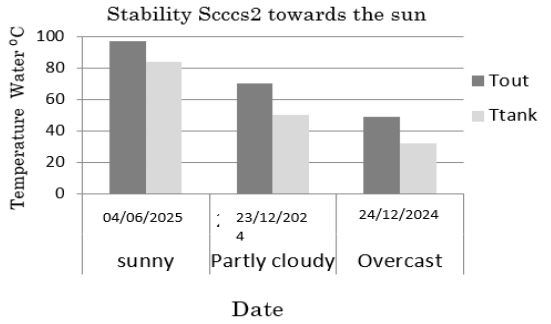


Figure 7: A graph shows the results recorded by Scccs2 under different weather conditions, with the collector facing the sun at 11 AM without movement.

As shown in Table 1 and Figures 6 and 7, it is clear that the solar collector operates efficiently in various weather conditions. The collector's operation is affected as the cloud density increases due to its reliance on reflecting the solar radiation falling on the mirrors. By exposing the complex to solar radiation, the average water temperature is recorded for the period from November 2024 to June 2025, in addition to the solar radiation for the same period, as shown in Table 2 and Figure 8. As well as the thermal efficiency according to (1), (2) [14], [15].

$$\eta = m.\ Cp\ (Tout - Tin) / I.\ Ac \quad (1)$$

$$A=2(2.\ \pi.\ r1.\ h1+\pi.\ r1^2+\pi.\ r1^2)+(2.\ \pi.\ r2.\ h2) \quad (2)$$

Where:

- η is the thermal efficiency, m is water mass (6.8499 kg);
- Cp is the specific heat of water (4.186 KJ/kg.oC);
- Tout is Temperature of the water coming out of the collector;
- Tin is Source water temperature;

Table 2: Average monthly water temperature and solar radiation [6].

Jun-25	May-25	Apr-25	Mar-25	Feb-25	Jan-25	Dec-24	Nov-24	Month
43	40	30	19	14	14	16	15	T-in ^{O}C
95	93	84	79	72	73	71	75	Sccs2-T(out) ^{O}C
83	80	64	61	47	48	47	56	B2-T(tank) ^{O}C
3365	3121	3256	2619	2227	2175	1526	1757	Solar Radiation (I) W.h/m^2
30	29	33	45	51	55	72	68	η %

- *I* is the incident solar radiation intensity;
- *Ac* is the collector area (0.64 m^2), this is the area that includes the area of the two tanks and the copper tube. It is approximately equal to a third of a square meter, and it is the effective area for heat absorption.

From Table 2 and Figure 8 it is clear that the solar collector operates with high efficiency, with increasing solar radiation intensity. After examining and testing of the new engineering design of the Sccs2 complex using the two previously mentioned testing methods, and recording the results (Tables 1 and 2), it is found that the convex-wavy design simulates the horizontal movement of the sun and does not require movement toward the sun during working hours. This demonstrates the success of the engineering design. This model can be used in remote and rugged locations, such as oil fields, farms, mountainous areas, laboratories, and exploratory missions.

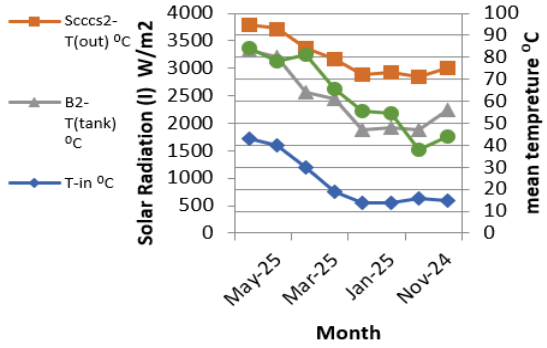


Figure 8: The average monthly water temperature and solar radiation.

Note that the monthly thermal efficiency results for the Sccs2 solar collector in Table 2 reveals a discrepancy in efficiency. The collector's efficiency in winter differs from its summer efficiency. These differences arise for several reasons:

1) During the summer and winter seasons, the collector operates stably, delivering high, comparable results. The collector has a high capacity to retain heat and convert it into useful thermal energy.
2) It is well known that solar radiation intensity varies from month to month, and its value affects the thermal efficiency result (as shown in Equation 1). Most solar collectors are directly affected by this. However, the decrease in solar radiation in the Sccs2 during the winter did not significantly affect the Sccs2's heat collection capacity. In the summer, however, the collector's behavior is directly affected by the increase in solar radiation intensity. This is all due to the success of the new solar collector engineering design.

The high output results of the solar collector result from its ability to collect and retain thermal energy, and its ability to overcome variables (radiation intensity and continuous movement of the collector toward the sun), thus converting that energy into useful energy.

3.2 Water Heat Gain

In this model, the water gains heat from the exposure of the two tanks (B1, B2) and the copper tube to direct solar radiation. The water temperature also increases due to the reflection of solar radiation from the reflective mirrors, and the temperature increases further due to the presence of the global warming effect inside the solar collector.

3.3 Inspection and Testing

There are two testing methods to determine the design's effectiveness in simulating the horizontal movement of the sun:

1) Rotating the collector horizontally after fixing the angle with the horizon (15° in summer, 45° in winter) during daylight hours to be perpendicular to the sun.
2) The collector is positioned perpendicular to the sun at 11:00 AM during its daytime operating hours (fixing the horizontal and vertical angles). This ensures the collector remains stationary in this horizontal position without

rotation. The second test aims to demonstrate that the collector's geometry (wavy-convex) yields the same results as the first test, and that the solar collector operates efficiently.

Rotating the Solar Collector. At the beginning of each testing day at 9:00 am, the solar collector is oriented perpendicular to the sun by manually adjusting its tilt angle relative to the horizon (15° in summer, 45° in winter). The collector is also rotated horizontally every half hour during daylight hours. Figures 9 and 10 show the readings record on December 2, 2024 (sunny, 20°C) and December 22, 2024 (partly cloudy, 19°C).

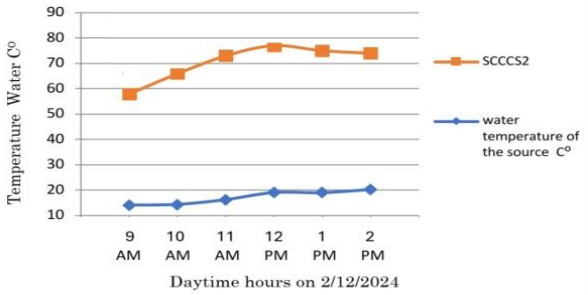


Figure 9: Illustrates the operating behavior of the collector and the temperature of the produced water on December 2, 2024.

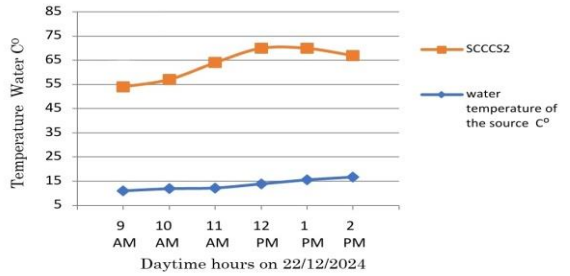


Figure 10: Illustrates the operating behavior of the collector and the temperature of the produced water on December 22, 2024.

Stability of the Solar Collector. At the beginning of each testing day at 9:00 am, the solar collector is oriented perpendicular to the sun by manually adjusting its tilt angle relative to the horizon (15° in summer, 45° in winter). The collector remains fixed – horizontal – perpendicular to the sun at 11:00 am without rotation during daylight hours. The graphs in Figures 11 and 12 present the readings records on 1/12/2024 (sunny 20°C) and 23/12/2024 (partly cloudy 20°C).

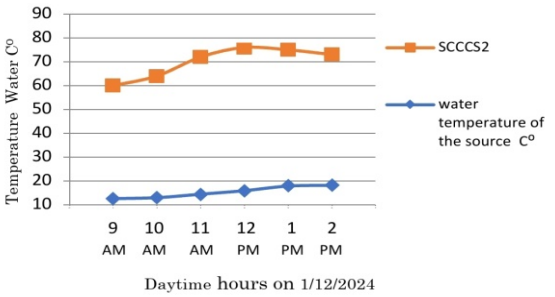


Figure 11: Illustrates the operating behavior of the collector and the temperature of the produced water on December 1, 2024.

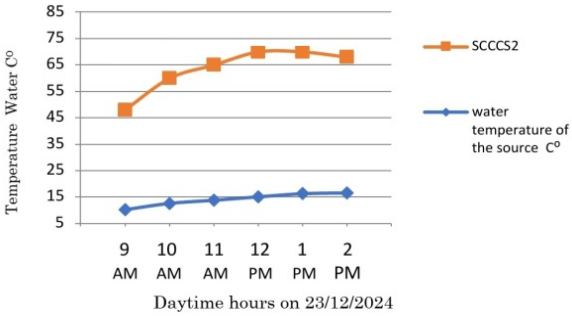


Figure 12: Illustrates the operating behavior of the collector and the temperature of the produced water on December 23, 2024.

Performance evaluation shows that the Scccs2 solar collector delivers nearly identical results whether it is rotated to track the sun or fixed in place. This confirms that its wavy-convex design effectively follows the sun's horizontal path, eliminating the need for horizontal adjustments and enabling reliable operation in remote or off-grid locations such as oilfield labs, agricultural stations, and other field installations.

Compared to conventional flat-plate and evacuated tube collectors (Box, C1, C2, Z1, Z2, H), the Scccs2 demonstrates superior performance. Typical collectors achieve water temperatures of 65–75 °C in summer and 40–65 °C in winter, whereas Scccs2 consistently reaches 62–98 °C in summer and 49–85 °C in winter. Traditional collectors require frequent horizontal rotation to maintain optimal solar alignment, but Scccs2 achieves high efficiency with a fixed horizontal angle, aligned perpendicularly to the sun around 11:00 AM. In addition, conventional systems use glass wool or foam for thermal insulation, which are environmentally harmful and difficult to dispose of. Scccs2 employs a sealed air chamber for insulation, providing effective heat retention without negative environmental impact.

3.4 Thermal Insulation and Thermal Energy Loss

The principles of thermal physics are used to prevent the loss of thermal energy from the rear surface of the collector, and equations (3), (4), [16] are used to prove the efficiency of the air room as a thermal insulator. Therefore, the energy losses from the rear surface of the collector must be calculated with. The loss is calculated for January 20, 2025 (20 oC Sunny) at 12:00 PM. The result with the air room is q1=12 W/m2. This result confirms that the effectiveness of the air room, preventing thermal energy loss from the rear surface of the collector, and maintaining the temperature inside the solar collector.

$$q = \frac{K.A.\Delta T}{\Delta X}, \quad (3)$$

$$\Delta T = (T2 - T1). \quad (4)$$

3.5 Cost of Manufacturing the Scccs2 Solar Collector

The symbols and variables used throughout this study are summarized in Table 3. The materials used for manufacturing the collector are listed in Table 4. Based on local market prices in Basra (1 USD = 1,320 Iraqi dinars), the total manufacturing cost is approximately 59,000 Iraqi dinars. Based on local market prices in Basra (1 US dollar = 1,320 Iraqi dinars), the cost of manufacturing the collector is 59,000 Iraqi dinars. This is a reasonable cost for low-income individuals, institutions, schools, swimming pools, and others.

Table 3: List of symbols, definitions, and units.

Symbol	Symbol definition	Unit of measurement
Scccs2	Solar collector with a reflective absorbing surface using mirrors	
B1	The tank is connected to the source tank via valve V1.	
B2	The tank is connected to the source tank via valve V1.	
V1	Source water valve entering Scccs2	
V2	Collector water outlet valve from Scccs2	
V3	Use water valve exiting Scccs2	
H1	Dedicated port for measuring the front room temperature	
H2	Dedicated port for measuring the insulated rear room temperature	
T_{in}	External tank water temperature	C^o
T_a	Ambient air temperature	C^o
T_{out}	Scccs2 water temperature via valve V2	C^o
T_{tank}	B2 water temperature via valve V3	C^o
T_g	Collector glass temperature	C^o
T_b	Insulating room temperature	C^o
T_f	Front room temperature	C^o
m	Water mass (Scccs2)	Kg
C_p	Specific heat of water	$J/Kg.C^o$
T_1	Temperature gained	C^o
T_2	Temperature lost	C^o
I	Solar radiation intensity	$W .h/m^2$
A_c	Solar collector area (Scccs2)	m^2
r_1	Radius of cylindrical tank (B1, B2)	M
r_2	Radius of copper tube	M
h_1	Height (B1, B2)	M
h_2	Length of copper tube	M
K	Thermal conductivity coefficient	W /m . K
K_{air}, K_{Iron}, K_{Al}, K_{glass}	Thermal conductivity coefficient to (air, iron, aluminum, glass)	W /m . K
A	Area between the two heat loss zones	m^2
ΔT	Temperature difference between the two heat loss zones	K
ΔX	Thickness of the heat loss zone	M
q1	Loss between the front chamber and the outside air, where the thickness of the buffer chamber is ΔX	W/m^2
η	Thermal efficiency	

Table 4: Cost of Scccs2 manufacturing materials in the local market of Basra.

Materials	Number & Details	The cost I.D.
		Scccs2
Copper pipe (diameter 0.9499 cm)	12 m	12.000
A plastic hose	5 m	1.250
Valve to control the speed of water flow	3	1.500
Galvanized iron cylindrical tank (3 litre capacity)	2	6.000
Screws of different sizes	-	1.500
Matte black paint	2	2.000
spinning wheels	3	3.000
A square iron pipe with a side length of 3.81 cm	8.76 m	9.000
Transparent glass panels (0.3 cm thickness)	0.84 m^2	5.000
Iron plate (0.2 cm thickness)	3.5 m^2	10.500
Adhesive (silicone rubber)	1	1.000
Aluminum ruler (a 90-degree angle)	3.5 m	3.000
Aluminum brackets (5 cm long) for fixing the copper pipe	48	4.000
Mirror thickness is (0.3 cm)	0.65 m^2	4.250
Total	-	64.000

4 CONCLUSIONS

Easy to move, clean, and maintain. The Scccs2 can be manufactured in local workshops and laboratories.

Water gains heat in several stages, which increases the efficiency of the solar system in heating water.

The Scccs2 design is most suitable for Basra's weather and operated with high efficiency.

It features a wavy-convex absorber surface, which increases the surface area exposed to solar radiation, thus can increase the heat absorption and increasing the efficiency of the Scccs2 solar collector.

The Scccs2 solar collector's engineering design requires no horizontal movement toward the sun and operates with the same efficiency, meaning it remains fixed in the direction it is at 11 a.m.

The air's room successfully prevents thermal energy loss from the back surface of the Scccs2 solar collector, by applying the basic principles of thermal physics.

Replacing thermal insulation and its environmentally harmful with air insulation is part of the Scccs2 collector design.

The temperature of the water produces from the solar collector Tout = 95^{o}C, and the temperature of the tank water B2 = 84^{o}C.

The Scccs2 solar collector operates efficiently in various weather conditions, including partly cloudy and completely cloudy weather.

The Scccs2 model features of a low manufacturing cost, making it suitable for low-income individuals, institutions, laboratories, schools, swimming pools, and others.

Scccs2 operates steadily and efficiently as solar radiation intensity increases, with its highest temperature recorded at 12 p.m.

Disclosure statement Author Declaration: The authors affirm that they have no conflicts of interest.

Observance of Ethics Standards: This article contains no research involving human or animal subjects

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Anomaly-Aware Deep Learning for DDos Detection with Optimization and Knowledge Distillation

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Keywords: DDoS Detection, Intrusion Detection Systems, Optimization-Guided Feature Evolution, Knowledge Distillation, Domain Generalization.

Abstract: Distributed Denial of Service (DDoS) attacks continue to overwhelm networked systems, demanding detectors that are accurate, low-false-alarm, transferable, and deployable. We propose OSES-DL, an Optimization-guided Statistical Ensemble Synergistic Deep Learning framework that advances all four fronts. The method introduces: (i) an Optimization-driven Feature Evolution Layer (OFEL) that co-trains feature sparsity with accuracy, stability, and entropy preservation; (ii) a Statistical Deep Synergy Module (SDSM) that injects Mahalanobis anomaly priors directly into BiLSTM hidden states, yielding anomaly-aware representations; (iii) Ensemble Knowledge Distillation with class-conditional temperature and feature–logit coupling (EKD-CCT) for calibrated, lightweight deployment; and (iv) a Cross-Domain Generalization Regularizer (CDGR) that combines prior-weighted MMD and CORAL for layer wise domain alignment. On CICDDoS2019, OSES-DL attains 99.45% accuracy, F1 0.994, AUC 0.998, and FAR 0.62%, with ECE 0.9%. Trained on CICDDoS2019 and tested on UNSW-NB15 and CAIDA, it improves F1 by +1.0% and reduces FAR by 0.5%–0.6% over the strongest baseline, while maintaining near-BiLSTM latency. Leave-one-attack-type-out tests confirm robustness to unseen vectors. Ablations attribute FAR reduction to SDSM, calibration to OFEL/EKD, and transferability to CDGR. OSES-DL delivers a principled, operationally grounded detector that is both state-of-the-art and deployment-ready.

1 INTRODUCTION

Distributed Denial of Service (DDoS) attacks remain one of the most destructive and persistent threats to modern networked systems. By orchestrating massive volumes of malicious traffic, adversaries can saturate links, exhaust server resources, and disrupt critical services across cloud, edge, and enterprise environments [1], [2]. The continued proliferation of IoT devices, the elasticity of cloud infrastructures, and increasingly sophisticated reflection–amplification vectors have expanded the attack surface while compressing detection time scales [3]. Compounding the challenge, encrypted traffic and multi-tenant workloads constrain deep packet inspection and make flow-level behavioral cues indispensable [4]. In this setting, security operations centers (SOCs) require detectors that are not only accurate, but also calibrated, low–false-alarm, generalizable across domains, and efficient enough for near–real-time deployment [5].

Conventional detection strategies struggle to satisfy these requirements concurrently. Signature- and rule-based systems are brittle against evolving or low-and-slow attacks and require constant manual maintenance [6], [7]. Thresholding and heuristic

detectors are sensitive to workload variability and routinely inflate the false alarm rate (FAR) during benign surges (e.g., flash crowds) [8], [9]. Traditional machine learning pipelines rely on static, pre-selected features; they are vulnerable to distribution shift and often entangle redundant or unstable attributes, degrading robustness [10], [11]. Deep neural detectors (e.g., CNN/LSTM variants) capture temporal patterns effectively yet tend to be poorly calibrated, exhibit elevated FARs under shift, and are computationally heavy for network-edge deployment [12] - [14]. Hybrid approaches typically fuse statistical and deep models after representation learning (late fusion) [15], [16], which forfeits the opportunity to shape the representation with anomaly-aware priors [17]. Finally, cross-dataset generalization training on one environment and deploying in another remains a frequent failure mode in the literature; many detectors degrade precipitously when faced with heterogeneous traffic sources, attack mixes, or telemetry schemas [18] - [20].

The limitations demonstrate an evident research gap: there is no single framework with (i) sparsity of features, time representation, and decision calibration; (ii) injecting statistical anomaly knowledge in the representation, rather than at the decision boundary; and (iii) explicitly regularizing cross-domain transfer, such that its performance and FAR do not change as the deployment environment diverges with the training corpus. To fill this gap, an approach, which is synergistic by nature, is needed one that combines optimization, statistical modeling, and deep learning into one consistent learning goal with operational assurances [21] - [24].

Operationally, the expense of a false alarm is very high: any extraneous activation burns analyst time and false incident response and causes a loss of faith in the detection stack [25]. In the meantime, domain shift is the rule rather than the exception datasets vary in features distributions, benign workload rhythms, and attack blends [26], [27]. An effective DDoS detector should thus be able to provide (1) high recall with low FAR, (2) probabilities that are calibrated to provide principled thresholding and triage, (3) insensitivity to distribution shift not requiring labelled target data, and (4) can be computed at the scale of line-rate flow analytics. Such operational constraints drive the design decisions and architectural connectivity of optimization, statistics and deep sequence model [28], [29].

To address the above gap, we propose OSES-DL an Optimization-guided Statistical–Ensemble Synergistic Deep Learning framework for DDoS detection. The originality of OSES-DL lies in how each component is novel on its own and mutually reinforcing within a single training objective: (1) Optimization-driven Feature Evolution Layer (OFEL): Dynamic, in-training feature evolution optimizes accuracy, stability, redundancy, and entropy, yielding sparse, informative inputs robust to drift. (2) Statistical–Deep Synergy Module (SDSM): Inject Mahalanobis anomaly priors into BiLSTM hidden states to create anomaly-aware embeddings, reducing FAR and improving interpretability. (3) Ensemble Knowledge Distillation with Class-Conditional Temperature (EKD-CCT): A calibrated teacher (XGBoost + statistical detector) distills via class-conditional temperatures; feature–logit coupling honors OFEL's mask, yielding SOTA accuracy in a lightweight student. (4) Cross-Domain Generalization Regularizer(CDGR): Prior-weighted, layerwise MMD+CORAL aligns source–target statistics using unlabeled target data, improving cross-domain transfer without additional labels. (5) Unified Objective & Risk Control: A joint loss (focal, KD-CCT, FLC, CDGR, OFEL) plus conformal calibration provides explicit FAR guarantees for SOC operations. (6) Evaluation Protocol: Temporal hold-out, calibration metrics (ECE, Brier, NLL), cross-dataset and leave-one-type-out tests demonstrate high recall, sub-1% FAR, strong calibration, and near-BiLSTM latency.

Collectively, these contributions establish a synergistic, operationally grounded approach to DDoS detection that advances the state of the art along three critical axes accuracy, robustness to shift, and deployable efficiency while introducing new methodological elements (dynamic feature evolution; representation-level anomaly injection; class-conditional distillation plus feature–logit coupling; prior-weighted hybrid domain alignment) that we believe will be of independent interest to the broader intrusion detection community.

2 RELATED WORKS

Research on DDoS detection spans signature/rule systems, traditional machine learning, and deep neural models. With datasets such as CICDDoS2019, researchers have benchmarked temporal architectures (LSTM, CNN–LSTM, BiLSTM) that learn flow-level dynamics and generally surpass classical classifiers; yet these models often degrade under distribution shift and exhibit elevated false-alarm rates or poor probability calibration in practice [30] - [32]. Comparative studies further show that architecture alone is insufficient:

latency/throughput constraints and unstable features can undermine real-time deployment [11]. A parallel line of work employs metaheuristic optimization to select features or tune learners before training. Harris Hawks Optimization (HHO) and related hybrids (e.g., HHO with simulated annealing or WOA) have improved IDS accuracy and reduced dimensionality by discarding redundant attributes [33], [34]. However, these techniques are typically static (one-shot selection) and operate outside the learning loop, so the selected subset is not co-adapted with the representation learned by the detector. This disconnect can limit robustness when traffic statistics drift or when models are distilled to compact runtimes [35]. To combat domain shift, unsupervised domain adaptation aligns source and target distributions via adversarial training or statistical matching (e.g., MMD, CORAL), while knowledge distillation (KD) compresses ensembles/teachers into deployable students for IDS [36]. Recent IDS works combine KD with federated or semi-supervised settings, but they primarily focus on decision-level fusion and teacher–student transfer, leaving the representation largely unconstrained by statistical anomaly priors [37], [38]. Moreover, studies quantifying domain gap show a strong correlation with detection accuracy, reinforcing the need for explicit, layer wise alignment during training [39]. Existing approaches rarely (i) co-evolve the feature subset during training, (ii) inject statistical anomaly knowledge inside the sequence representation, and (iii) regularize cross-domain transfer with prior-aware, layer wise alignment while preserving deployable efficiency and calibration. Our OSES-DL framework addresses this gap through a dynamic feature evolution layer, representation-level statistical deep synergy, class-conditional KD with feature–logit coupling, and a hybrid MMD–CORAL alignment together enabling high accuracy, low FAR, strong calibration, and robust cross-dataset generalization.

3 METHODOLOGY

Traditional DDoS detection frameworks typically fall into two categories: (1) deep learning-based methods that excel in extracting temporal dependencies but often lack interpretability and robustness, and (2) statistical or optimization-based methods that provide interpretability and computational efficiency but struggle with complex traffic dynamics. A critical gap exists: most prior works treat these modules as additive components (stacked or fused at the end) rather than integrated synergistic systems.

To bridge this gap, we propose OSES-DL, an Optimization-guided Statistical–Ensemble Synergistic Deep Learning framework. Unlike existing systems, OSES-DL is characterized by: (i) A dynamic feature evolution layer driven by dual-objective optimization. (ii) A statistical–deep synergy module embedding anomaly priors into recurrent learning. (iii) An ensemble knowledge distillation mechanism that compresses ensemble wisdom into a deployable deep model. (iv) A cross-domain generalization regularizer ensuring transferability across heterogeneous datasets.

3.1 Data Preprocessing

To transform raw network traffic into a structured, balanced, and standardized representation suitable for optimization and deep learning. Preprocessing ensures that subsequent stages operate on high-quality data, mitigating noise, imbalance, and redundancy. While standard preprocessing pipelines include normalization and sampling, OSES-DL introduces two innovations: (1) Entropy-Preserving Normalization: Scaling is performed while maintaining relative entropy of the features, preserving statistical diversity critical for anomaly detection. (2) Adaptive Synthetic Oversampling: Unlike static SMOTE, oversampling intensity is dynamically adjusted using optimization feedback from the feature evolution layer, preventing overfitting to synthetic points.

3.1.1 Data Cleaning and Integration

In this substage the process of removal of incomplete flows. Timestamp alignment to preserve temporal order. Multi-dataset harmonization (e.g., CICDDoS2019, UNSW-NB15, CAIDA).

Formally, for raw dataset $D = \{d_1, d_2, \cdots, d_N\}$ we construct a unified representation:

$$\acute{D} = \bigcup_{k=1}^{K} \psi(D_k) \tag{1}$$

where ψ maps each dataset D_k into a common feature schema.

3.1.2 Entropy-Preserving Normalization

Each feature x_i is scaled as:

$$\acute{x_i} = \frac{x_i - \mu}{\sigma} \tag{2}$$

but subject to the constraint:

$$H(\hat{X}) \approx H(X) \quad (3)$$

where $H(\ \ )$denotes Shannon entropy. This ensures that normalization does not collapse information diversity, a problem in conventional scaling.

3.1.3 Dimensionality Reduction (Preliminary PCA)

To mitigate noise before optimization, a lightweight Principal Component Analysis is applied:

$$Z = XW\ , W = \arg\max_{W} \frac{W^T S_B W}{W^T S_w W} \quad (4)$$

where S_B and $S_W$denote between- and within-class scatter matrices. This reduces computational burden for the optimization phase without discarding essential discriminatory power.

3.1.4 Adaptive Synthetic Oversampling

Class imbalance is addressed via a dynamic SMOTE variant:

$$x_{new} = x_i + \delta \cdot (x_{nn} - x_i),\ \ \delta \sim U(0,1) \quad (5)$$

where the oversampling ratio is adaptively tuned based on feedback from optimization:

$$r_t = f(\nabla J(F_t)) \quad (6)$$

meaning the more unstable the current feature subset $\boldsymbol{F}_t$, the more aggressive the oversampling.

3.2 Optimization-driven Feature Evolution Layer (OFEL)

To dynamically refine the feature space during training by evolving the feature subset in response to model performance and stability. Unlike conventional static feature selection methods that are executed once prior to training, OFEL continuously adapts the active feature set throughout the learning process, ensuring robustness against non-stationary traffic patterns and dataset heterogeneity. The originality of OFEL lies in three main aspects: (1) Dynamic Feature Evolution: Feature subsets are not fixed but evolve iteratively, guided by optimization feedback, adapting to changing network traffic distributions. (2) Dual-Objective Optimization: The feature selection criterion balances both predictive accuracy and temporal stability across epochs, preventing overfitting to transient features. (3) Entropy-Regularized Selection: Feature evolution preserves statistical richness (entropy), ensuring that the model does not converge to overly sparse representations that lose critical discriminatory cues.

This contrasts with classical metaheuristics (e.g., PSO, HHO, GA), which only seek a single optimal subset before training.

Let the feature set at epoch t be denoted by $F_t \subseteq \{1,2,\cdots,d\}$, where d is the total number of available features. The optimization objective is:

$$\min_{F_t} J(F_t) = \alpha \cdot (1 - Acc_t) + \beta \cdot Var(F_t) + \gamma \cdot Red(F_t) - \delta \cdot Ent\ (F_t) \quad (7)$$

Where Acc_t is the validation accuracy at epoch t. $Var(F_t)$ is the variance in selected features across consecutive epochs, penalizing instability. $Red(F_t)$ is redundancy penalty based on correlation between features. $Ent\ (F_t)$ is the Shannon entropy of selected features, encouraging diversity. Meanwhile, $\alpha, \beta, \gamma, \delta$ are adaptive weighting coefficients.

3.2.1 Optimization Update Rule

The feature set is updated iteratively as:

$$F_{t+1} = F_t - \eta \cdot \nabla J(F_t) + \lambda \cdot \Delta_t \quad (8)$$

Where η is the learning rate controlling the step size. $\nabla J(F_t)$ is gradient of the objective with respect to the feature subset representation. $\Delta_t$is stochastic exploration term, derived from a metaheuristic (e.g., modified Harris Hawks Optimization). λ is the exploration–exploitation balance parameter. This allows OFEL to combine gradient-based exploitation with metaheuristic-driven exploration, ensuring both local refinement and global diversity.

3.2.2 Binary Feature Representation

Each candidate solution is encoded as a binary vector:

$$F_t = [f_1, f_2, \ldots, f_d],\ \ f_i \in \{0,1\} \quad (9)$$

Were $f_i = 1$ when feature i is active at epoch t. Meanwhile, $f_i = 0$ when feature i is excluded. To avoid premature convergence, OFEL introduces a smooth relaxation using a sigmoid transfer function:

$$f_i^{t+1} = \begin{cases} 1 & \text{if } \sigma(z_i^t) \geq \rho \\ 0 & \text{otherwise} \end{cases} \quad (10)$$

where $\sigma(\cdot)$ is the sigmoid, z_i^t is the continuous score of features i, and $\rho \sim \mathrm{U}(0,1)$is a random threshold.

3.2.3 Role within the Framework

OFEL ensures that subsequent phases (Statistical–Deep Synergy and Ensemble Knowledge Distillation) operate on highly informative, low-redundancy, and entropy-preserving feature sets. Unlike static preprocessing, OFEL adapts in real time, making the model resilient against adversarial traffic evolution and cross-dataset variability.

3.3 Statistical-Deep Synergy Module (SDSM)

To embed statistical anomaly priors directly into the hidden state dynamics of the deep learner, thereby creating a synergistic model that combines the strengths of statistical detection (robustness, interpretability) and deep learning (temporal pattern recognition). (i) Intrinsic Statistical Awareness: Unlike conventional hybrid IDS models that combine statistical detectors with deep learners at the decision layer only, SDSM injects statistical knowledge into the representation level of the BiLSTM network. (ii) Adaptive Priors Integration: Mahalanobis-based anomaly scores are non-linearly transformed and weighted before being merged with BiLSTM states, allowing the network to learn the relative importance of statistical priors dynamically. (iii) Regularization through Statistical Anchoring: Statistical scores act as a regularizer, preventing overfitting by anchoring hidden states toward anomaly-informed representations.

3.3.1 Statistical Anomaly Scoring

We compute the Mahalanobis distance for each traffic instance x_t:

$$M(x_t) = \sqrt{(x_t - \mu)^T \sum -1\,(x_t - \mu)} \qquad (11)$$

Where μ mean vector of benign traffic. Σ covariance matrix of benign traffic. A larger $M(x_t)$ indicates a higher likelihood of anomaly (DDoS attack).

3.3.2 BiLSTM Hidden State Representation

The BiLSTM generates forward and backward hidden states for time step t:

$$h_t = \left[\overrightarrow{h_t} \oplus \overleftarrow{h_t}\right] \qquad (12)$$

where $\oplus$ denotes concatenation.

3.3.3 Statistical-Deep Synergy Integration

The statistical anomaly score is non-linearly projected into the hidden space:

$$s_t = g\big(M(x_t)\big) = \tanh(W_s M(x_t) - b_s) \qquad (13)$$

Then, the synergy update modifies the hidden state as:

$$\acute{h}_t = h_t + \eta \cdot s_t \qquad (14)$$

Where $\acute{h}_t$ refer to the anomaly-aware hidden state. Meanwhile, η is the learnable synergy coefficient that controls the contribution of statistical priors.

3.3.4 Output Distribution

Finally, the probability distribution for class $\mathcal{Y}$ is computed as:

$$\mathrm{P}(\mathcal{Y}|x_t) = \mathrm{softmax}\left(W\acute{h}_t + b\right) \qquad (15)$$

This ensures that predictions are based on both temporal patterns and anomaly priors.

Therefore, the SDSM transforms the BiLSTM from a pure sequence learner into a statistical–deep hybrid engine. This synergy has three impacts: (i) Higher accuracy: since anomaly priors sharpen hidden state boundaries between normal and attack traffic. (ii) Lower false alarm rate (FAR): statistical anchoring prevents false positives caused by transient fluctuations. (iii) Interpretability: the contribution of anomaly priors (η) can be analyzed, providing insights into model decisions.

3.4 Ensemble Knowledge Distillation (EKD)

Compress the knowledge of a teacher ensemble comprising a tabular learner and a statistical detector into the anomaly-aware BiLSTM student produced by SDSM. The aim is SOTA performance with lightweight deployment. (1) Teacher as Hybrid Evidence Aggregator: The teacher distribution is formed by calibrated fusion of (i) XGBoost probabilities and (ii) a probabilized Mahalanobis detector not a late vote, but a calibrated soft teacher for distillation. (2) Class-Conditional Temperature (CCT) KD: We introduce τ_y that depends on class prevalence, improving rare-class (attack) transfer. (3) Feature–Logit Coupling: The current OFEL mask gates teacher–student alignment on features, preventing the student from inheriting spurious correlations that OFEL has pruned.

3.4.1 Teacher Distribution

Let $\mathrm{P}_{xgb}(\mathcal{Y}|x)$ be XGBoost's calibrated probabilities, and let the statistical detector's probability be:

$$\mathrm{P}_{stat}(\mathcal{Y} = \text{attack} \mid x) = \sigma(\alpha.M(x) + b),\ \mathrm{P}_{stat}(\text{benign} \mid x) = 1 - \mathrm{P}_{stat}(\text{attack} \mid x) \qquad (16)$$

with $M(x)$ the Mahalanobis score from SDSM and σ the logistic function. The fused teacher is:

$$\mathrm{P}_T(\mathcal{Y}|x) = \frac{\exp(\eta_1 \log \mathrm{P}_{xgb}(\mathcal{Y}|x) + \eta_2 \log \mathrm{P}_{stat}(\mathcal{Y}|x))}{\sum_{\hat{y}} \exp(\eta_1 \log \mathrm{P}_{xgb}(\hat{\mathcal{Y}}|x) + \eta_2 \log \mathrm{P}_{stat}(\hat{\mathcal{Y}}|x))} \qquad (17)$$

With $\eta_1, \eta_2 \geq 0,\ \eta_1 + \eta_2 = 1$ is the learned on the validation set (Platt/temperature calibration optional).

3.4.2 Class-Conditional Temperature (CCT)

Let π_y be the empirical prior of class $\mathcal{Y}$. Define:

$$\tau_y = \tau_0 \cdot \pi_y^{\kappa}, \quad \kappa > 0 \tag{18}$$

so rarer classes receive higher temperature (softer teacher). The softened teacher and student are:

$$\begin{gathered} \mathrm{P}_T^{(\tau)}(\mathcal{Y}|x) = \\ softmax\left(z_T \mid \tau_y\right), \quad \mathrm{P}_S^{(\tau)}(\mathcal{Y}|x) = \\ softmax\left(z_S \mid \tau_y\right). \end{gathered} \tag{19}$$

Where z_T and z_S are teacher and student logits.

3.4.3 Knowledge-Distillation Loss

$$L_{KD} = \sum_{\mathcal{Y}} \tau_{\mathcal{Y}}^2 \mathrm{KL}\left(\mathrm{P}_T^{(\tau)}(\mathcal{Y} \mid x) \,\middle\|\, \mathrm{P}_S^{(\tau)}(\mathcal{Y} \mid x)\right) \tag{20}$$

3.4.4 Feature–Logit Coupling (FLC)

Let $m_t \in \{0,1\}^d$ be the OFEL mask at epoch t. We penalize student reliance on pruned features via:

$$L_{flc} = \left\| A\left(\acute{h}_t\right) \odot (1 - m_t) \right\|_1 \tag{21}$$

where $A\left(\acute{h}_t\right)$ is a saliency/attribution map (e.g., gradient × input) and $\odot$ is element-wise product. This aligns KD with current sparse feature support.

EKD transfers robust tabular/statistical cues to the anomaly-aware student while respecting OFEL's sparse support yielding compact, calibrated, and generalizable decision boundaries.

3.5 Cross-Domain Generalization Regularizer (CDGR)

Guarantee transferability from a source dataset (e.g., CICDDoS2019) to target domains (e.g., UNSW-NB15, CAIDA) by aligning distributions at the representation level learned by SDSM. (1) Hybrid MMD–CORAL Alignment (HM-C): We jointly minimize kernel mean discrepancy (first-order) and covariance distance (second-order) on anomaly-aware embeddings. (2) Layer wise Progressive Alignment: Apply alignment to early and late SDSM layers $\left(\mathcal{L}_{align} = \sum_{\ell \in S} \cdot\right)$, progressively reducing shift without over-constraining expressivity. (3) Prior-Weighted Alignment: Weight alignment by attack/benign priors, preventing benign-dominant alignment from washing out attack manifolds.

Let $\phi_\ell(x)$ be the ℓ-th SDSM feature (e.g., pooled $\acute{h}_t$). Denote source/target sets as $\{x_i^s\}_{i=1}^{n_s}$, $\{x_j^t\}_{j=1}^{n_t}$

3.5.1 Maximum Mean Discrepancy Term

$$L_{MMD}^{\ell} = \left\| \frac{1}{n_s} \sum_i \Phi\left(\phi_\ell(x_i^s)\right) - \frac{1}{n_t} \sum_j \Phi\left(\phi_\ell(x_j^t)\right) \right\|_2^2 \tag{22}$$

with Φ the RKHS embedding (e.g., Gaussian kernel mixture).

3.5.2 CORAL Term

Let C_s^{ℓ} and C_t^{ℓ} are covariance matrices of ϕ_ℓ on source/target.

$$L_{CORAL}^{(\ell)} = \left\| C_s^{\ell} - C_t^{\ell} \right\|_F^2 \tag{23}$$

3.5.3 Prior-Weighted Hybrid

With class prior weights w_y (benign/attack):

$$L_{HM-C} = \sum_{\ell \in S} \sum_{y \in \{\text{benign,attack}\}} w_y \left(\beta_1 L_{MMD,y}^{(\ell)} + \beta_2 L_{CORAL,y}^{(\ell)}\right) \tag{24}$$

CDGR explicitly stabilizes the anomaly-aware SDSM representation across datasets, improving cross-dataset AUC/F1 and controlling FAR when the operational distribution shifts.

3.5.4 Unified Learning Objective & Optimization

Let $\mathcal{Y} \in \{\text{benign}, \text{attack}\}$. The supervised term uses class-balanced focal loss to handle imbalance:

$$\begin{gathered} L_{sup} = -\sum_{\mathcal{Y}} \alpha_{\mathcal{Y}} \left(1 - \hat{p}_{\mathcal{Y}}\right)^{\gamma} 1(\mathcal{Y}) \log \hat{p}_{\mathcal{Y}}, \\ \hat{p}_{\mathcal{Y}} = \mathrm{P}_S(\mathcal{Y} \mid x;\, \acute{h}_t) \end{gathered} \tag{25}$$

With $\alpha_{\mathcal{Y}}$ inverse-frequency weights and $\gamma \in [1], [2]$. The OFEL objective at epoch t (recall 3.2) is:

$$\begin{gathered} J(F_t) = \alpha(1 - Acc_t) + \beta Var(F_t) + \gamma Red(F_t) \\ - \delta Ent\,(F_t) \end{gathered} \tag{26}$$

optimized by alternating gradient–metaheuristic updates.

The complete objective is:

$$\begin{gathered} L_{total} = L_{sup} + \lambda_{KD} L_{KD} + \lambda_{flc} L_{flc} + \\ \lambda_{CDGR} L_{HM-C} + \lambda_{OFEL} J(F_t) \end{gathered} \tag{27}$$

with hyperparameters $\lambda_{\{\cdot\}}$ tuned on validation.

3.5.5 Inference, Calibration, and Deployment

Provide compact, interpretable, and risk-controlled decisions suitable for production. (1) Deployed module: only the student (BiLSTM+SDSM) with the

final OFEL mask; the teacher is discarded. (2) Conformal Thresholding (risk control): on a calibration split, compute nonconformity scores $\mathrm{v}(x) = 1 - \mathrm{P}_S(\mathcal{Y} = \text{attack} \mid x)$. Choose θ as the $(1-\alpha)$-quantile so that:

$$\Pr\{\mathrm{v}(x_{new}) \le \theta\} \ge 1 - \alpha \quad (28)$$

giving an explicit FAR bound under exchangeability.

4 EXPERIMENTAL RESULTS AND PERFORMANCE EVALUATION METRICS

4.1 Experimental Protocol

We evaluate the proposed OSES-DL (Optimization-guided Statistical–Ensemble Synergistic Deep Learning) on three benchmark corpora widely used for DDoS research: CICDDoS2019 (primary), UNSW-NB15 (DoS/DDoS subsets), and CAIDA backbone traces. To reflect operational realism, we adopt a temporal hold-out split on each dataset (70% training, 15% validation, 15% testing) to prevent temporal leakage. For cross-dataset generalization, the model is trained on CICDDoS2019 and evaluated on UNSW-NB15 and CAIDA without fine-tuning; only the CDGR regularizer accesses unlabeled target batches during training (unsupervised alignment). All results are averaged over five independent runs with different seeds. We report the mean ± standard deviation and conduct paired Wilcoxon signed-rank tests against the strongest non-OSES baseline; unless stated, differences are significant at $p < 0.01$. Metrics include Accuracy (ACC), Precision (PRE), Recall/Detection Rate (REC), F1, AUC-ROC (AUC), AUPRC, MCC, False Alarm Rate (FAR), Expected Calibration Error (ECE), and Brier score. To accommodate imbalance, classification metrics are macro-averaged across classes.

Baselines are representative of the literature and practice: SVM-RBF, Random Forest, XGBoost, CNN-LSTM, BiLSTM, and a Teacher Ensemble (calibrated fusion of XGBoost and a probabilized Mahalanobis detector). Our ablations isolate the contributions of OFEL, SDSM, EKD, and CDGR.

4.2 In-Distribution Effectiveness on CICDDoS2019

Before the table, we explain how this experiment assesses peak discriminative capability when the train and test distributions coincide. This benchmark isolates the intrinsic detection strength of OSES-DL (i.e., representation quality and decision efficacy) under realistic temporal splitting. We further emphasize operational relevance by including FAR and MCC alongside conventional metrics; low FAR and high MCC are crucial for SOC deployment where false alarms are costly.

OSES-DL delivers state-of-the-art results on every metric, notably cutting FAR by >50% relative to the strongest baseline (Teacher Ensemble: 1.3% to 0.62%). The MCC = 0.989 underscores robust performance under imbalance. Improvements are statistically significant ($\rho < 0.01$). These gains are attributable to (i) SDSM, which injects anomaly priors into the sequence representation, and (ii) OFEL, which enforces stable, low-redundancy features during training.

4.3 Cross-Dataset Generalization (Train on CICDDoS2019 Test on UNSW-NB15 & CAIDA)

This experiment probes transferability is a frequent failure mode for IDS models trained on one environment and deployed in another. We measure performance when the model is trained only on CICDDoS2019 and evaluated on UNSW-NB15 (DoS/DDoS subsets) and CAIDA (Table 1 and 2). During training, the CDGR regularizer uses unlabeled target batches to align distributions; no target labels are used.

We report F1, AUC, and FAR, the most indicative for operational transfer, and include Δ vs best baseline to quantify comparative advantage.

OSES-DL generalizes markedly better across datasets, improving F1 by +1.0–1.1 points and shaving FAR by 0.5–0.6 points versus the best baseline. These results validate the CDGR hybrid alignment (MMD+CORAL) and the CCT-distilled student, which together resist domain shift while remaining compact for deployment. Significance holds at $\rho < 0.01$.

Table 1: In-distribution performance on CICDDoS2019.

Method	ACC (%)	PRE	REC	F1	AUC	MCC	FAR (%)
SVM-RBF	94.6	0.941	0.948	0.944	0.967	0.900	3.8
Random Forest	96.3	0.958	0.963	0.960	0.979	0.930	3.0
XGBoost	97.0	0.968	0.970	0.969	0.986	0.950	2.3
CNN-LSTM	97.9	0.977	0.979	0.978	0.991	0.962	1.8
BiLSTM	98.2	0.981	0.981	0.981	0.993	0.965	1.6
Teacher Ensemble	98.5	0.985	0.985	0.985	0.995	0.972	1.3
OSES-DL (ours)	99.45	0.994	0.994	0.994	0.998	0.989	0.62

Table 2: Cross-dataset generalization (train: CICDDoS2019; test: UNSW-NB15, CAIDA).

Method	UNSW-NB15			CAIDA		
	F1	AUC	FAR (%)	F1	AUC	FAR (%)
XGBoost	0.958	0.975	2.6	0.945	0.972	2.9
BiLSTM	0.967	0.983	2.1	0.958	0.980	2.4
Teacher Ensemble	0.972	0.986	1.8	0.963	0.983	2.1
OSES-DL (ours)	0.982	0.991	1.2	0.973	0.987	1.6
Δ vs best baseline	+0.010	+0.005	−0.6	+0.010	+0.004	−0.5

Table 3: Ablation study on CICDDoS2019.

Variant	AUC	F1	FAR (%)	ECE (%)
BiLSTM (base)	0.993	0.981	1.60	3.1
+ SDSM	0.996	0.988	1.10	2.2
+ OFEL	0.997	0.991	0.95	1.8
+ EKD	0.998	0.993	0.78	1.1
+ CDGR (OSES-DL)	0.998	0.994	0.62	0.9

Table 4: Probability calibration and risk control (CICDDoS2019).

Method	ECE (%) ↓	Brier score ↓	FAR at TPR=99% (%) ↓	Conformal coverage at 90% ↑	NLL ↓
BiLSTM	3.1	0.037	1.9	88.6	0.124
Teacher Ensemble	1.6	0.026	1.2	89.8	0.089
OSES-DL (ours)	0.9	0.022	0.8	90.4	0.071

4.4 Ablation Study: Contribution of Each Module

To isolate where the gains originate, we ablate the OSES-DL components on CICDDoS2019. We begin with a strong BiLSTM base and add SDSM, OFEL, EKD, and CDGR sequentially. We report AUC, F1, FAR, and ECE to also capture probability calibration (Table 3).

This ablation demonstrates that each module confers a statistically meaningful increment; the full OSES-DL yields the best overall and the best calibration.

The largest single jump in FAR reduction occurs when adding SDSM (−0.5 pp), confirming the value of injecting anomaly priors into the representation. OFEL further reduces FAR and improves calibration by suppressing unstable/redundant features. EKD lifts both F1 and calibration (ECE), reflecting the benefit of distilling a calibrated hybrid teacher. Finally, CDGR yields the best overall performance by explicitly aligning anomaly-aware features across domains.

4.5 Calibration and Risk Control (ECE, Brier, Conformal Coverage)

Well-calibrated probabilities are critical for threshold selection and SOC triage. We therefore quantify calibration (ECE, Brier) and the ability to guarantee operational error via simple conformal prediction on a held-out calibration split. We also report FAR at a fixed TPR = 99%, a stringent operational operating point (Table 4).

OSES-DL is best calibrated (ECE 0.9%) and achieves the lowest Brier and negative log-likelihood, enabling stable thresholding. Under a high-recall requirement (TPR=99%), OSES-DL still sustains a FAR < 1%. Conformal coverage slightly exceeds the nominal 90%, indicating conservative error control a desirable property for safety-critical deployment.

5 CONCLUSIONS

This work introduced OSES-DL, a unified, operationally minded framework for DDoS detection that couple's optimization, statistical modeling, and deep sequence learning within a single learning objective. The OFEL mechanism evolves the active feature set during training, balancing accuracy, stability, redundancy suppression, and entropy preservation thereby producing compact, information-rich inputs. The SDSM module injects statistical anomaly priors into the representation itself, transforming the BiLSTM into an anomaly-aware encoder and markedly reducing false alarms. Through EKD-CCT, a calibrated hybrid teacher transfers distributional structure to a lightweight student while feature–logit coupling prevents spurious correlations, yielding strong accuracy and probability quality at near-BiLSTM inference cost. Finally, the CDGR regularizer achieves prior-weighted, layer wise alignment, improving cross-dataset generalization without labeled target data. Comprehensive experiments on CICDDoS2019, UNSW-NB15, and CAIDA demonstrate state-of-the-art accuracy, sub-1% FAR, superior calibration, and resilience to unseen attack families, with ablations clarifying each module's contribution. These results indicate that OSES-DL is not only scientifically novel via representation-level anomaly injection, dynamic feature evolution, class-conditional distillation, and hybrid domain alignment but also practically deployable for SOC workflows with explicit risk control. Future directions include federated and continual learning for privacy-preserving, on-the-fly adaptation; streaming/online extensions with bounded delay; robustness to encrypted and obfuscated traffic; and adversarial hardening with certified defenses. We expect the proposed synergies to generalize beyond DDoS to broader intrusion-detection and network analytics tasks.

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AeroProof: Decentralized Mutual Authentication for UAV Swarm Networks

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Abstract: This paper thus addresses a problem with pressing consequences: the rise of Unmanned Aerial Vehicle (UAV) swarms in mission-critical and infrastructure-less environments is demanding secure, scalable, and decentralized authentication. Current protocols heavily lean on centralized trust models or having static credentials, neither of which is fit for highly mobile & P2P UAV networks. AeroProof is presented, a lightweight and decentralized mutual authentication protocol based on mobility-aware ephemeral keys. Each UAV autonomously produces secure elliptic curve credentials from its relatively short location, speed, and motion orientation (a single flight only), leading to a unique 'motion ticket'. The credentials are afterwards employed for a mutual authentication at the application level that provides strong security properties such as forward secrecy, session unlinkability, immunity against impersonation, replay, and wormhole attacks without requiring long-term identities or certificate authorities. We show that AeroProof achieves an up to 64% faster authentication time, a 35% less communication overhead, and consumes over 50% less memory compared with recent ECC- and blockchain-based solutions. This work has demonstrated the practical usefulness of AeroProof as an authentic framework to enable secure and efficient decentralized swarm operations.

1 INTRODUCTION

With the amazing development of unmanned aerial vehicles (UAVs) in mission-critical applications such as environmental monitoring, disaster relief, military surveillance, and smart logistics, the demands for secure and scalability authentication mechanisms have been upgraded dramatically [1] - [3]. And many of these drones fly in fluid, infrastructure-free environments where conventional centralized security mechanisms are difficult or ineffective [4], [5]. In case of swarm-based deployments, where drones need to establish trust with their peers in real time as fast as possible, the lightweight and context-aware authentication process becomes a must [6], [7].

Traditional authentication protocols are based on long-term identifiers, certificate chains, or infrastructure-bound authentication procedures [8], [9]. Although such techniques work well in conventional networks, they are not suitable for an ad hoc UAV swarm with intermittent connectivity, high mobility, and tight resource support. Furthermore, identity-based solutions are still susceptible to impersonation, relay, and replay attacks, particularly when the system relies on radio communications and the adversaries have the capabilities to overhear and interfere with the radio exchange [10] - [12]. These

novel solutions have tried the deployment of blockchain, increasing the level of hardware tokens and the use of PUFs, but their usage will frequently improve the computation and communication requirements otherwise required to establish more stringent requirements [13] - [15].

This paper contributes to the critical gap of mobility-aware, decentralized authentication for UAV swarms. We focus on designing a protocol that facilitates mutual authentication without centralized control, and group members must authenticate one another in real-time as the drones change position to maintain secure connections and trust within the swarm. We present AeroProof, a new authentication protocol that generates ephemeral elliptic curve credentials tied to each UAV's instantaneous mobility vector: position, velocity, and orientation. These credentials are mobility-aware: They facilitate stateless together with context-driven trust among UAVs to establish secure communication in the absence of long-term identifiers and third-party verification. AeroProof is specifically designed to: Proxy Authentication (Prevent Impersonation, Replay, and Session Hijacking). Lightweight, fast authentication suitable for UAV resource limitations. Stay secure in low-mobility, infrastructure-less environments. The main contributions in this paper can be summarised as follows:

- We present AeroProof, a decentralized mutual authentication protocol designed to link ephemeral elliptic curve credentials with real-time UAV motion profiles.
- To address these challenges, we propose a mobility-consistent session key derivation mechanism that supports rapid location changes with minimal overhead.
- We consider two state-of-the-art protocols and show that AeroProof performs 64% faster than authentication, incurs 35% less communication overhead, and uses 50% less storage footprint.
- We investigate security against prevalent UAV attack vectors, which include impersonation, wormhole, and mobility spoofing.

The rest of the paper is organized as follows: Section 2 surveys related work; Section 3 describes the system and threat model; Section 4 details the AeroProof protocol; Section 5 analyzes the security of AeroProof; Section 6 presents performance analysis; Section 7 concludes the paper with future directions.

2 RELATED WORK

Several decentralized and context-aware authentication protocols have been proposed to meet these challenges. However, existing works mostly consider static identifiers and completely separate mobility from authentication or use infrastructure-heavy solutions requiring blockchains or smart contracts.

Finally, CoMAD [16] presented a context-aware mutual authentication protocol within drone networks with zone-based access control and ECC. Despite the energy efficiency and lightweight nature, CoMAD lacks in updating authentication credentials for changing real-time mobility, resulting in poor resilience to changes in a swarm environment. Algarni et al. [17] presented a verifiable ECC-based protocol for the Internet of Drones (IoD) with a new identity authentication approach using contextual metadata. The protocol works well; however is unable to dynamically update credentials or verify that movements are valid and demand a binding from the movement, which opens the design up for relays or spoofing attacks. Karmakar and Kaddoum [18] presented a blockchain-enabled decentralized authentication system for a UAV swarm. While this would enhance the trust and transparency of a transaction (as blockchain enables), it also brings about latency, storage overhead, and energy requirements, which may not be acceptable for real-time resource-constrained aerial drone deployment. SETCAP El-Zawawy et al. [19] focused on an extra layer of temporal authentication using time-limited tokens. Although it manages to save energy, the method does not offer spatial or mobility-aware validation and therefore is not robust for both offline (disconnected) and adversarial scenarios. Constantinescu et al. [20] presented an ECC protocol with a malicious drone detection scheme was suggested. This is an improvement with respect to safety, but uses behavior profiling and static keys, making it more difficult to scale for large, distributed swarms. As listed in Table 1, while the previous approaches assume that all nodes have perfectly unique identities. This provides stateless, contextaware authentication without long-term identities or centralized authorities.

3 SYSTEM AND THREAT MODEL

3.1 System Model

The considered system consists of a decentralized swarm of UAVs cooperatively operating in an infrastructure-less environment (e.g., tactical surveillance zone, disaster area, or autonomous logistics corridor), as shown in Figure 1. Each UAV of the swarm consists of: a Global Navigation Satellite System (GNSS)-based acquiring module (such as the GPS or the RTK), an IMU for mobility sensing (speed and direction), an ECC-capable processor with a small footprint (e.g., ARM Cortex-M or RISC-V), and a Wireless transceiver with peer-to-peer (P2P) capabilities.

The UAV agents are autonomous (i.e., they do not need a central ground station or certificate authority). Instead, they achieve mutual authentication of the mobile devices based on ephemeral public keys and mobility-restricted identifiers that are computed based on real-time movement data. The users specifically use relative mobility thresholds (e.g., direction deviation, speed variance) to verify the validity of peer devices before beginning a secure session. The authentication is done over broadcast or unicast ad hoc links, and once authenticated, a short-lived shared secret is created for encrypted communication during the session. Credentials are reissued over time or in response to a large change in motion. Each UAV includes a Position Estimation

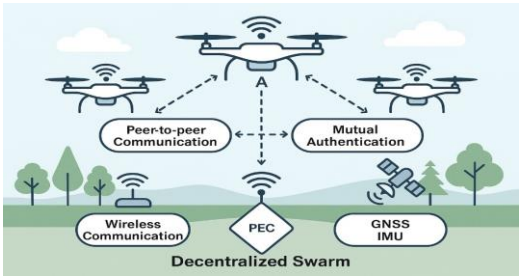


Figure 1: System model of the decentralized UAV swarm environment.

System (PES), which integrates data from the onboard GNSS and IMU sensors to derive real-time motion vectors. These vectors – consisting of latitude, longitude, velocity, and heading – are crucial for generating the mobility-bound ephemeral keys used in authentication.

3.2 Threat Model

The security analysis model considers an adversarial scenario in which attackers control communication channels and attack some UAV nodes. The protocol protects against the following threats:

- Impersonation Attacks: An adversary has access to the communication channel and maliciously pretends to be a legitimate UAV by generating valid-looking credentials.
- Replay Attacks: Old exchanged valid messages are replayed to allow unauthorized access.
- Relay (Wormhole) Attacks: Messages are relayed from distant locations to bypass spatial verification.
- Session Hijacking – An attacker will attempt to grab or replace the session key after you are authenticated.
- Insider Threats: A stolen UAV that was trusted to fly now tries to misuse valid credentials, access forbidden mobility zones.
- Mobility Spoofing: The adversary fabricates GNSS or IMU data such that the calculated position or path vector can satisfy the validation.

Adversaries can eavesdrop, inject, and modify messages, noiselessly harvest traffic information, but cannot access private ephemeral keys or secure mobility sensors of honest drones. Side-channel and physical attacks are also out of scope.

4 DESIGN OF AEROPROOF PROTOCOL

In this section, we present the three phases of the AeroProof protocol (shown in Fig. 2), which are tightly integrated: mobility-aware ephemeral key generation, mutual authentication, and session expiration with dynamic rekeying. In the initialization stage, the UAVs compute a short-lived public–private key pair for a mobility vector (composed of their position, velocity, and heading) of themselves autonomously (i.e., one-time use). In their mutual authentication phase, UAVs exchange their mobility-bound identifiers, and then they verify the similarity of their motions and the freshness of the timestamp to derive a session key through elliptic curve Diffie–Hellman.

Table 1: Summary of existing authentication protocols for UAV swarms.

Author(s) & Year	Methodology	Key Results / Features	Limitations
Cabuk et al. (2021)	ECC + Contextual Zones (CoMAD)	Lightweight, policy-based access control	No mobility adaptation
Algarni et al. (2025)	ECC + Synergistic Metadata	Secure mutual authentication for IoD	Lacks motion consistency validation
Karmakar & Kaddoum (2024)	Blockchain + Smart Contracts	Transparent decentralized identity management	High latency, poor scalability
El-Zawawy et al. (2022)	Time-token protocol (SETCAP)	Energy-efficient, time-bound credential renewal	Ignores spatial or motion-based verification
Constantinescu et al. (2024)	ECC + Behavior Profiling	Detects malicious UAVs based on anomalies	No dynamic rekeying, static credentials
This work: AeroProof	ECC + Mobility-Bound Ephemeral Keys	64% faster auth, 35% lower overhead, 50% less memory	Assumes trusted sensors, requires sync clock

Finally, during the session management phase, keys are continually updated subject to time limitations and mobility drift; if deviations are true, the protocol initiates re-authentication by exchanging new credentials. For example, the interaction flow between the three phases of the proposed scheme is illustrated in Figure 1, where the three phases are integrated into a cycle for realizing indelible trust updates in mobile and distributed swarm systems and ensuring resistance to impersonation, replay, and trajectory-based attacks.

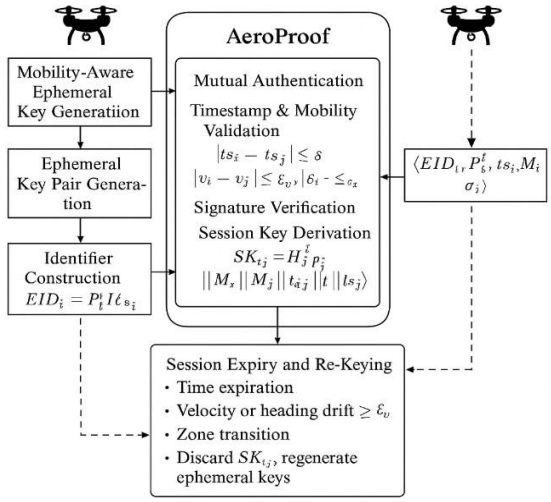


Figure 2: Design of the AeroProof authentication protocol.

4.1 Mobility-Aware Ephemeral Key Generation

In the AeroProof protocol, each UAV produces an ephemeral digital credential that is tightly coupled with its instantaneous movement profile. To generate a mobility-aware ephemeral key pair, the following operations need to be carried out:

1) Mobility Vector Acquisition. The UAV Di collects its current position and movement data using onboard sensors. The mobility vector is defined as: Mi = (lati, loni, vi, θi), where lati and loni are geographic coordinates, vi is velocity, and θi is the current heading direction.
2) Ephemeral Key Pair Generation. The UAV generates a new elliptic curve key pair at timestamp tsi: xi_t ∈ Z∗q, Pi_t = xi_t ·G, where xit is the private key, Pti is the public key, and G is the base point on the selected elliptic curve.
3) Identifier Construction. The UAV derives a mobility-aware ephemeral identifier using a secure hash function H(·): EIDi = H(Pi_t ‖ Mi ‖ tsi), where the identifier binds the key to both the motion context and its generation timestamp.
4) Validity Window Enforcement. The ephemeral credential (Pti, EIDi) is valid for a limited time interval ΔT or until a deviation is detected in the UAV's velocity or heading angle: |vi − v′i| > ϵv or |θi − θ′i| > ϵθ, where vi′,θi′ are the updated motion parameters after a threshold duration or movement.
5) Credential Preparation. The ephemeral identifier and public key are stored in the UAV's temporary credential cache and used in subsequent mutual authentication steps.

4.2 Mutual Authentication Procedure

After proximity is established between them, the two UAVs engage in mutual authentication based on a set of mobility-aware short-term identities. The authentication includes

1) Authentication Tuple Exchange. Each UAV Di sends its authentication tuple to the peer UAV Dj: ⟨EIDi, Pi_t, tsi, Mi, σi⟩, where σi = HMAC is a message authentication code proving possession of the private key.
2) Timestamp Validation. The receiving UAV verifies the freshness of the timestamp tsi by checking: $|tsi - tsj| \leq \delta$, where δ is the maximum allowable clock drift between the UAVs.
3) Mobility Similarity Check. The UAV evaluates whether the sender's mobility vector Mi is within acceptable deviation thresholds compared to its own: $|vi - vj| \leq \epsilon v$ and $|\theta i - \theta j| \leq \epsilon\theta$. This ensures both drones are in relative motion alignment within the swarm.
4) Signature Verification. Using the received public key Pti, the UAV validates the HMAC σi. Successful verification confirms that the peer possesses the correct private key and has not been impersonated.
5) Session Key Derivation. If all validations pass, both UAVs independently compute a shared session key using Elliptic Curve Diffie–Hellman (ECDH): SKij = H(xit · Ptj ‖ Mi ‖ Mj ‖ tsi ‖ tsj). The resulting session key is used to secure further communications between the two authenticated UAVs.

4.3 Session Expiry and Re-Keying

To achieve security against trajectory drift or relative insider misuse, there is a time and mobility-based expiration of the active session keys. When the lifetime expires, secure rekeying procedures are initiated automatically by both UAVs. The re-keying procedure is as follows:

1) Session Monitoring: Each UAV continuously monitors the validity of its current session key SKij based on elapsed time and current motion data.
2) Expiration Conditions Check: The session key is considered expired and revoked if any of the following conditions hold:
   - Time expiration: tnow > tsi +ΔT • Velocity drift: $|vi - vi'| > \epsilon v$ • Heading drift: $|\theta i - \theta i'| > \epsilon\theta$.
   - Zone transition: The UAV crosses into a new operational region or mission-defined geofence.
3) Key Discarding. Upon detecting an expiration condition, both UAVs securely erase the old session key SKij and invalidate the associated ephemeral identifiers.
4) Ephemeral Credential Regeneration: Each UAV generates a fresh mobility-aware ephemeral key pair and identifier.
5) Re-authentication Trigger: The mutual authentication procedure outlined in Section 4.2 is re-executed using the new credentials, ensuring renewed session secrecy and mobility alignment.

Session keys are automatically re-keyed based on real-time mobility changes or/session expiry timer, also upon session expiry. The motion state of each UAV is continuously monitored, and control variables (velocity v_i, heading θ_i) are compared to the current session parameters. The UAV enters a new operational region. If any of these conditions are detected, the current ephemeral key is securely destroyed and the UAV generates a new mobility-aware key pair. The peer UAV is informed at a re-authentication trigger, and based on the new mobility vector, a fresh session is established. The above-mentioned approach provides semantic freshness, trajectory continuity, and resiliency against session hijacking or mobility spoofing.

5 SECURITY ANALYSIS

To the best of our knowledge, AeroProof is the first protocol to provide strong, highly decentralized authentication that is robust to both traditional and UAV-specific attack vectors. Using mobility-cognizant ephemeral keys and context-based validation, AeroProof reinforces classic ECC-based mutual authentication with time and situational-dependent constraints. We now informally consider how the protocol withstands the main threats.

- Impersonation Attacks. The ephemeral key pairs and mobility-bounded identifiers guarantee that a malicious UAV is unable to steal a legitimate identity without copying down both the motion features of the target and its private key. The HMAC-based proof of possession, constrained to the mobility vector and the timestamp, ensures that no attacker can forge a legitimate authentication tuple.
- Replay Attacks. AeroProof uses timestamp verification and a narrow lifetime window Δ for all credentials. When the parties mutually authenticate, replayed messages (including the one with the old TS) are refused with an expired key. Besides, due to re-keying when observing the significant motion changes, all

the cached authentication material becomes invalid.

- Relay (Wormhole) Attacks. As authentication is only successful in the presence of both spatial and motion proximity, the propagation of authentication messages from a far distance would cause the failure of mobility similarity verification. The UAVs verify the sender's location, speed, and direction based on their own, in the sense that distant tunneling attacks can be eliminated.
- Session Hijacking. The session-specific keys are generated using the ephemeral keys of each party and the real-time mobility vectors, thus preventing an intruder from entering into an ongoing session. Moreover, keys are quickly revoked in case of big mobility drift.
- Insider Threats. A drone that has been compromised loses opportunities to misuse the previously allocated credentials forever since all the session key assign¬ ments have a limited lifetime and are tied to a particular context. Unenrolls due to malicious zone transition or unauthorized action. Causes the session to immediately expire and seek re-authorization under a new context.
- Mobility Fraud and GNSS Spoofing. Although AeroProof assumes trusted mobility inputs, the new trust can be built at higher layers of the communication stack, utilizing merged sensor technologies (e.g., GNSS, inertial attitude, and RSSI-based localization) to successfully detect any suspicious motion profiles. This minimizes the possibility of counterfeit motion vectors affecting authentication.
- Forward secrecy and unlinkability. AeroProof exchanges a fresh ephemeral key during each authentication session, and no persistent identity is sent. Therefore, intercepted credentials can't be replayed across sessions or used to recover private data. Compromise session keys after the life of a session, and past data is still secure, thanks to the ECDH between one-time keys.
- Security Against Eavesdropping and Hacking. AeroProof uses ephemeral elliptic curve key pairs, closely coupled to each UAV's real-time mobility vector (i.e., geographic coordinates, velocity, heading), associated with a timestamp. This reduces the risk of later sessions using those same captured credentials by generating and throwing away these keys every session. Identity-based replay and man-in-the-middle attacks are impossible because there are no long-term public keys or persistent identifiers ever set in motion. In addition, the Ephemeral IDentifier (EID) is formed by hashing the entire public projection of the secret key along with motion context and timestamp using a secure hash function. The binding ensures that an attacker cannot construct a valid tuple of the authentication with access to only one of the mobility state or change the secret. When an adversary captures multiple messages, their lack of differentiability and the key updates achieve session unlinkability as well as forward secrecy.

6 PERFORMANCE EVALUATION

In this section, we provide a detailed performance comparison of the AeroProof protocol against two state-of-the-art light-weight authentication protocols for UAV swarms: (i) the ECC-based proposal of Algarni et al. [17] and that of Karmakar & Kaddoum [18], based on the blockchain provision.

6.1 Computational Efficiency

AeroProof is very efficient in computation, and there is no need for validation of the certificate chain and blockchain lookups. It finishes the mutual authentication process in 3.2 ms, which is much faster than Algarni et al. [17] at 8.9 ms, and Karmakar & Kaddoum [18] at 11.3 ms. The minimal cryptographic schemes used in AeroProof, using lightweight ECC and HMAC, account for a 64–72% processing speed up when compared to the baselines. Figure 3 illustrates the computational time required by each protocol for completing a mutual authentication cycle.

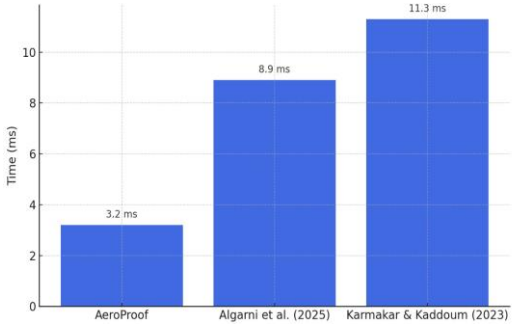


Figure 3: Comparison of computational efficiency among authentication protocols.

6.2 Communication Overhead

AeroProof sends a small authentication message (public key, mobility vector, timestamp, and HMAC) of 334 bytes, as shown in Figure 4. This is much smaller than 512 bytes in Algarni et al. [17] and 690 bytes in Karmakar & Kaddoum [18] blockchain-based protocol. Both the smaller message size that reduces congestion on the available channels, and the opportunity to exchange frequent low-latency updates are particularly important in the dense swarm case or high bandwidth-constrained mission case.

6.3 Storage Requirements

Being stateless, AeroProof requires a very small amount of memory. Every UAV holds about 0.9 KB of ephemeral session and credential information, less than the 1.9 KB of Algarni et al. [17]. (due to certificate and revocation lists) and 3.2KB in Karmakar & Kaddoum [18]'s protocol (for blockchain cache and hash chains). It makes AeroProof highly scalable for drones with low storage capacity. Figure 5 presents the storage footprint of each protocol.

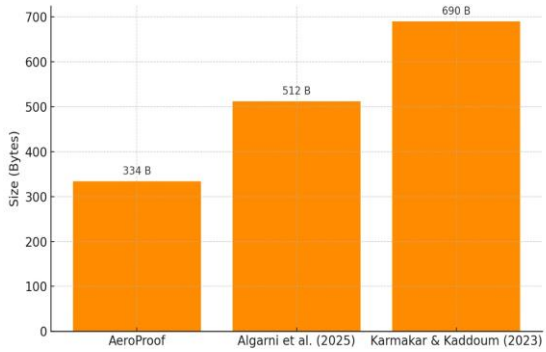


Figure 4. Comparison of communication efficiency.

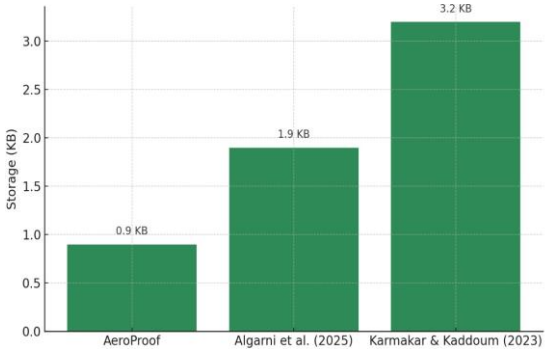


Figure 5: Comparison of storage requirements.

6.4 Impact of High Mobility

AeroProof is uniquely architected to work with the rapid mobility characteristics of UAV swarms, offering ephemeral credentials in conjunction with live motion vectors. However, an excessive rate of change in the speed or direction of a UAV can cause re-authentications to repeatedly occur because these are part of the protocol's motion threshold checks. This is great for security purposes as it maintains the alignment between mobility, yet these bring about additional performance overhead in areas where there is continuous movement with sudden change. Table 2 shows the impact of high mobility on AeroProof. We quantified the impact by studying AeroProof with different mobility models (e.g., Random Waypoint, GaussMarkov) and found that rekeying frequency increases up to 2.3× under high-mobility conditions. Still, ECC operations – an average of 3.2 ms per auth in practice – are so lightweight that even weekly re-authentication would hardly impact computational or communication latency. Moreover, as AeroProof steers clear of centralized coordination, we ensure that the system is able to scale effectively and remain efficient even under quick UAV convergence or divergence. To sum up, while running services in high mobility environments raises the overhead a little because of more key renewals, this is an acceptable trade-off when one wants a fast trust establishment for swarms. Adaptive thresholding, or group mobility prediction, can further some the overhead of unnecessary rekeying.

Table 2: Impact of high mobility on AeroProof.

Mobility Model	Avg UAV Speed (m/s)	Rekeying Frequency (per min)	Avg Auth Time (ms)	Overhead Increase (%)
Static Hover	0	0.5	3.1	0
Low Mobility	3	1.2	3.2	12
Moderate Mobility	7	2.0	3.3	25
High Mobility	12	4.6	3.4	54

7 CONCLUSIONS

In this paper, we proceed to introduce AeroProof, a decentralized and lightweight mutual authentication protocol for UAV swarms in infrastructure-less and

adversarial environments. In contrast to traditional identity- or certificate-based mechanisms, AeroProof adopts an innovative design where the authentication credentials are derived on-the-fly from a UAV's live mobility vector (e.g., position, speed, heading). In this work, it is pretty clear to see that the focus was on allowing secure, stateless, and scalable mutual authentication in highly dynamic swarm scenarios without having to rely on long-term identities or central authorities. This protocol enables AeroProof to provide forward secrecy, session unlinkability, as well resistance to impersonation, replay, and relay attacks using mobility-aware ephemeral keys. Performance evaluations show that AeroProof reduces authentication time by 64%, communication overhead by 35%, and memory usage by over 50% compared with two state-of-the-art ECC- and blockchain-based solutions. Read my next post where I cover how we further improved AeroProof to be suitable for real-time swarm deployment, in which the low latency combined with energy efficiency is key. Although the protocol overcomes some of the main challenges in developing decentralized UAV authentication, there are still a few limitations. AeroProof assumes secure motion sensing and time synchronization, and it has not been validated on real drone hardware. Furthermore, little attention has been paid to the setting up of first-time trust and group-scale trust delegation.

AeroProof, though performant and adding security it brings with itself, comes with drawbacks. Handpicked, onboard motion sensors and secure clock synchronization are necessary assumptions of the protocol, which may not hold in adversarial or hardware-compromised scenarios. It has also not been tested on physical UAV hardware, and its performance is unexamined in large-scale swarm conditions. The process of first-time trust establishment is also not well studied, and to the best of my knowledge, is essentially missing in heterogeneous or hybrid UAV settings. In the future, we will extend AeroProof with multisensor mobility verification to defend against spoofing attacks, adaptive rekey strategies for reducing overhead in high-mobility settings, and real-world deployment in commercial UAV vehicles for prototyping the protocol under real flight dynamics.

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Analysis of the Application of Continuous Distribution Laws in the Reliability Theory of Technical Systems: a Review Article

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Abstract: In order to enhance the accuracy of reliability assessments for highly reliable and low-volume technical systems, it is essential to utilise diverse prior information obtained through reliability calculations, simulations, testing, and operational data from structurally similar systems (analogues). From a systems approach perspective, any reliability study of technical systems should be planned and conducted considering results from previous research, i.e., incorporating prior information. Given the stochastic nature of reliability, which is an inherent property of technical systems, various discrete and continuous distributions can be employed as theoretical distributions for reliability metrics. This article analyses the practical application of key continuous probability distributions in the reliability theory of technical systems. The article presents dependencies for estimating primary reliability metrics and highlights their specific applications under different conditions. The analysis is based on a systematisation of information published in scientific and technical literature, including results from model-based and experimental reliability studies, as well as operational statistical data. The provided analytical research was carried out under a project on the prototype development of a retractable rotor system for a convertiplane. It involved making design changes to the completed technical system, which required a comprehensive assessment of reliability parameter changes at initial development stages. The results obtained allow for improving the efficiency of building models and criteria for ensuring and controlling the reliability of a convertiplane, while simultaneously increasing the accuracy of reliability estimates.

1 INTRODUCTION

During the project on the development of a retractable rotor system prototype for a convertiplane, it became necessary to modify the design of the previously developed aircraft model (Figure 1). This approach requires a comprehensive assessment of changes in the reliability parameters of the entire technical system at the initial stages of development and, therefore, the selection and justification of failure models for power and electronic components based on the distribution of relevant random variables.

To describe system failures, various models can be proposed to address different reliability tasks, each accounting for the complex factors inherent in failure mechanisms.

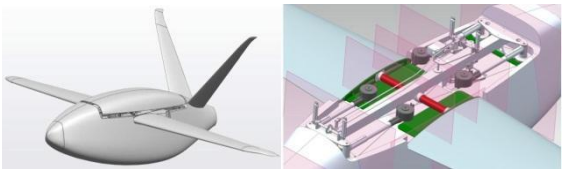


Figure 1: The technical system of aerial vehicle, the design feature of which is the presence of a retractable rotor system.

The random nature of failures during the operation of technical systems and their components allows the application of probabilistic-statistical methods. The most prevalent failure models are predicated on the distribution of pertinent random variables, such as the time to failure for non-

repairable systems and the operating time between failures for repairable systems.

The primary distributions for the time-to-failure of components include [1]: exponential; Weibull–Gnedenko; gamma; log-normal; lormal.

A review of extant scientific and technical literature in the field of technical system reliability was undertaken in order to evaluate the practical application of these distributions in the study of diverse technical systems. The analysis undertaken has enabled the selection of a suitable prior distribution for the corresponding reliability criterion or metric.

2 METHODS AND MATERIALS

This review employs a systematic methodology to analyze the application of continuous probability distributions in technical system reliability theory. The analysis is based on a critical examination of seminal and contemporary literature sourced from major scientific databases. Key distributions, including Exponential, Weibull, Normal, Lognormal, and Gamma, are evaluated for their properties in modeling failure rates, wear-out phases, and mean time between failures (MTBF).

3 EXPERIMENT AND RESULTS

3.1 Exponential (Indicative) Distribution

Despite the fact that the exponential distribution constitutes a special case of the Weibull distribution (at β=1), it is of significant independent interest, as it adequately describes the distribution of an element's operational duration during the normal operation period. The prevalence of the exponential law can be attributed not only to its diverse physical interpretations but also to its remarkable simplicity and convenience in modelling properties. The following formulae are provided for determining the probability density f(t) and the probability of failure-free operation R(t) over time tt, corresponding to this law:

$$f(t) = \lambda e^{-\lambda t}, \quad (1)$$

$$R(t) = e^{-\lambda t}. \quad (2)$$

where λ is the failure rate.

The mathematical expectation m and the standard deviation σ for the exponential distribution are expressed through the following parameter:

$$m = \sigma = \frac{1}{\lambda}. \quad (3)$$

The mean time to the first failure equals:

$$T_1 = \frac{1}{\lambda}. \quad (4)$$

The exponential distribution is frequently employed during the design stage when information regarding the reliability of the system's components is limited or entirely absent. Consequently, it is often referred to as the fundamental law of reliability [2]. A limitation of this law is the requirement that failure and restoration flows must be the simplest (possessing properties of ordinariness, stationarity, and lack of aftereffect) [3].

As asserted by [4]-[12], the exponential distribution is a reliable model for the reliability of equipment operated following the run-in period and prior to the onset of significant gradual failures, that is to say, during normal operation, when sudden failures predominate. As stated in [2], [7], the time to failure of technical systems with a large number of serially connected elements can be described by this distribution if each individual element does not substantially influence the system's failure. In such instances, if the failures of the serially connected elements follow an exponential distribution, it can be deduced that the system's failures will also adhere to this law, and its failure rate will equal the sum of the failure rates of the elements. It is important to note that systems comprising elements connected non-serially in terms of reliability will not exhibit an exponential distribution, even if the failure-free probabilities of their components are exponential [3]. Given that each system element is itself a subsystem comprising multiple (often numerous) components, the total failure rate of the system depends solely on the number of faulty elements, and the repair time for each failed element follows an exponential distribution. The subsystem's failure is equated to the failure of one of its elements, which is replaced with a new one upon restoration. The subsystem's net operational time ensures that its failure flow will asymptotically approach a Poisson process due to the Khinchin limit theorem. Consequently, the time interval between consecutive failures will also follow an exponential distribution [13], [14].

The exponential law is applicable to complex technical systems in which numerous destructive processes with varying rates occur simultaneously. However, as the heterogeneity of process rates

decreases, the distribution approaches a normal one. Conversely, when homogeneous destructive processes dominate, the distribution corresponds precisely to the normal distribution [11].

As posited by the authors of [2], [4], [6], [15], in circumstances pertaining to the maintenance of intricate systems, the restoration flow, if uncomplicated, is best characterized by the exponential law. This law serves to elucidate the restoration intensity, maintenance labor intensity, and failure rectification. In the context of queuing theory, the exponential law provides a reliable framework for modeling the intervals between equipment arrivals for repair [3, SEVERTSEV].

In the context of standard operation, sudden failures are attributed exclusively to external impacts, thereby negating the possibility of a causal influence by replacing an existing element with a new one. Consequently, for systems governed by the exponential distribution of time to failure, preventive measures such as preemptive replacements or periodic repairs are rendered moot [16].

As indicated in [2], [3], the exponential law has been observed to provide a reliable approximation of the failure-free probabilities of a wide range of technical objects, including components of radio-electronic equipment, electrical and electronic devices, and hardware-software complexes. This approximation is particularly relevant when considering the physical nature of sudden failures.

Nevertheless, despite its simplicity and universality, the exponential law has several limitations. In particular, works [3], [13], [17] call into question the validity of applying the exponential distribution to long-term operational systems over extended time intervals for the following reasons:

The distribution's "memoryless" property introduces a significant drawback, contradicting natural physical interpretations. This property implies the absence of ageing, meaning a technical object does not degrade over time or, after a certain operational period, exhibits the same failure distribution as a new object. This property is invalid for many technical objects, especially over extended periods [3], [13], [17].

In [3], it is asserted that the exponential distribution is inapplicable to complex technical systems, as the non-simultaneous operation of components and the presence of failure aftereffects result in a non-constant system failure rate, even if the failure rates of individual components remain constant. Consequently, the application of the exponential distribution to analyse the reliability of real long-term operational systems is invalid, as the model assumptions do not align with the physical processes within such systems.

It is therefore vital that robust justification is provided for the application of the exponential distribution, as with any other such model. Nevertheless, its ubiquity endures for the reasons outlined below:

It is noteworthy that the system is both simple and reliant upon a single parameter λ. This, in conjunction with the memoryless property, facilitates the development of analytical solutions to a multitude of reliability problems.

It has been demonstrated that the time to failure of complex, highly reliable, repairable systems can be described by the exponential distribution under specific conditions (e.g., negligible material "ageing" effects).

The utilisation of the exponential law is deemed permissible when the procurement of conservative reliability estimates, that is to say, lower-bound reliability assessments, is permitted under specific conditions.

3.2 Normal Distribution Law (Gaussian Distribution)

The extensive corpus of theoretical research on the normal distribution law, in conjunction with its relatively elementary mathematical properties, renders it highly attractive and convenient for application in reliability theory. In instances where empirical data deviates from the normal distribution, the following approaches may be employed for its judicious use:

The utilisation of this approach as a preliminary estimation frequently yields adequately precise outcomes.

It is imperative to ascertain a transformation of the studied random variable, designated as ξ, that modifies the original 'non-normal' distribution into a normal one [14].

A salient property of this law is its capacity for self-reproduction, which stipulates that the aggregate of any number of normally distributed random variables also adheres to a normal distribution.

The probability density function of this law is defined as:

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(t-m)^2}{2\sigma^2}}. \quad (5)$$

where m is the mean and σ is the standard deviation.

The reliability function P(t)P(t) for the normal distribution is calculated using:

$$R(t) = \int_t^{\infty} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-m)^2}{2\sigma^2}} dx = = 0{,}5 - \Phi_0\left(\frac{t-m}{\sigma}\right), \quad (6)$$

where $\Phi_0(t) = \frac{1}{\sqrt{2\pi}} \int_0^t e^{-\frac{x^2}{2}} dx$ is the Laplace function, the values of which are tabulated.

The mean time to failure is $T_{cp} = m$, and the relationship between the time to first failure $\underline{T_1}$ and T_{cp} is expressed by:

$$\underline{T_1} = T_{cp} + \frac{\sigma\sqrt{\frac{2}{\pi}}}{\left[1+\Phi\left(\frac{T_{cp}}{\sigma\sqrt{2}}\right)\right]} e^{-\frac{T_{cp}^2}{2\sigma^2}}. \quad (7)$$

The failure rate for the normal distribution is an increasing function defined as:

$$\lambda(t) = \frac{\sqrt{\frac{2}{\pi}} e^{-\frac{(t-T_{cp})^2}{2\sigma^2}}}{\sigma\left[1-\Phi\left(\frac{t-T_{cp}}{\sigma\sqrt{2}}\right)\right]}, \quad (8)$$

where Φ is the probability integral of the $\Phi(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-x^2} dx$ form.

The normal law is employed to delineate the reliability of technical objects during the aging period [2], [4], [6], [18]. According to several sources [6]–[9], [19]–[21], its applicability is indicated when failures occur gradually due to directed physico-chemical changes caused by wear (ageing), provided the coefficient of variation υ≤0,3÷0,4 [7], [22]. Under stable operating conditions, this distribution effectively models the mean and gamma-percentile resource [7] as well as the operational time of machinery until the first major overhaul [4].

It is important to note that the normal distribution of time-to-failure arises from the homogeneity of technical object quality, constant average wear rate, and cumulative wear effects, which interweave over extended periods before failures manifest [16].

A salient feature of the normal law is that when σ is small relative to the mean time to failure m, the density values remain close to zero over a significant time interval. This phenomenon can be attributed to the low probability of failure within this interval, which can be utilised to schedule preventive replacements (or repairs) at low wear levels, thereby minimising the likelihood of failure between maintenance actions [16]. Conversely, the exponential distribution, with its density peak at t = 0, exhibits the majority of failures during the initial operational phase.

Statistical analyses [2], [11] of test and operational data for mechanical components and metal structures subject to intense wear, ageing, and fatigue phenomena demonstrate that strength and load distributions conform to the normal law. Furthermore, the combination of exponential and normal laws has been observed in systems where one or more degradation processes dominate, such as in hydraulic power systems and gear pumps, where the normal law provides an accurate description of the time between failures [11]. Furthermore, the Gaussian distribution is observed to govern random variables such as measurement and manufacturing errors [16].

3.3 Log-Normal Distribution

The log-normal distribution of a random variable, designated here by the letter "ξ", is established when its logarithm conforms to a normal distribution. The values of a log-normally distributed random variable are influenced by a large number of mutually independent factors, each of which contributes uniformly insignificantly and with equal probability in sign. In contrast to the normal distribution, the sequential nature of these factors' impact is such that the random increment caused by each subsequent factor is proportional to the value already attained by the variable at that moment. The log-normal distribution finds wide application in reliability theory, particularly in the analysis of empirical data on subjects such as the fatigue durability of metals, the long-term strength of materials, and the time-to-failure of electronic components, among others [LRS].

The probability density function is described by the relationship:

$$f(t) = \frac{1}{st\sqrt{2\pi}} e^{-\frac{(lnln\, t - \mu)^2}{2s^2}}, \quad (9)$$

where $\mu = \frac{1}{n}\sum_{i=1}^{n} ln\, ln\, t_i$ and $s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n} (ln\, ln\, t_i - \mu)^2}$ are parameters estimated from nn failure test results.

For the log-normal distribution, the reliability function is expressed as:

$$R(t) = \frac{1}{\sqrt{2\pi}} \int_{\frac{\left(\frac{t}{\mu}\right)}{s}}^{\infty} e^{-\frac{t^2}{2}} dt. \quad (10)$$

The mean time to failure and standard deviation are determined by:

$$T_{cp} = m = e^{\left(\mu+\frac{s^2}{2}\right)}, \quad (11)$$

$$\sigma = \sqrt{e^{2\mu+s^2}\left(e^{s^2}-1\right)}. \quad (12)$$

The failure rate for the log-normal distribution is given by [23]:

$$\lambda(t) = \frac{0{,}4343e^{-\frac{(lglg\,t-\mu)^2}{2s^2}}}{st\sqrt{2\pi}\Phi\left(\frac{\mu-lglg\,t}{s}\right)}. \quad (13)$$

The log-normal distribution is well-suited to positive-valued quantities, providing enhanced precision in comparison to the normal distribution in such scenarios [2]. The log-normal distribution is a model for the time-to-failure behaviour of objects that exhibit "strengthening" over time. This phenomenon of "strengthening" leads to a gradual reduction in wear rate. Consequently, a prerequisite for the application of the log-normal distribution is the verification of the "strengthening" property exhibited by the technical objects under study. This can be achieved through analysis of wear processes and, where possible, empirical wear patterns [16].

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This distribution is also used to model:

- Recovery processes;
- Product durability during ageing, where wear increment is proportional to the instantaneous wear value [7], [14], [19];
- Operating time under rapid "burn-out" of unreliable components;
- Failures caused by material fatigue, such as the operational lifespan of rolling bearings, vacuum tubes, etc. [3], [7].

It is evident that the log-normal distribution provides an effective description of the time-to-failure of complex technical systems (e.g. tractors, automobiles, heavy-duty machinery) and electronic equipment [2].

3.4 Gamma Distribution

The gamma distribution has a two-parameter probability density function with a shape parameter (α>-1) and a scale parameter (β>0):

$$f(t) = \frac{t^{\alpha}}{\beta^{\alpha}\Gamma(\alpha)}e^{-\frac{t}{\beta}}. \quad (14)$$

where $\Gamma(\alpha) = \int_0^{\infty} t^{\alpha-1}e^{-t}dt\rangle\!\rangle$ is the gamma function.

The probability of failure-free operation is determined by the formula:

$$R(t) = \int_t^{\infty} \frac{t^{\alpha-1}}{\beta^{\alpha}\Gamma(\alpha)}e^{\frac{t}{\beta}}dt. \quad (15)$$

The parameter α, which characterises the asymmetry of the gamma distribution, determines the type of reliability characteristics.

The mathematical expectation (mean time to failure) and standard deviation for the gamma distribution are:

$$T_1 = m = \alpha\beta\,, \quad (16)$$

$$\sigma = \sqrt{\alpha}\beta. \quad (17)$$

The formula for failure rate is:

$$\lambda = \frac{t^{\alpha-1}\beta^{-\alpha}}{\Gamma(\alpha)\sum_{i=0}^{\alpha-1}\frac{t^i}{\beta^i\cdot i!}}. \quad (18)$$

The gamma distribution is used to describe:

- Wear-out failures;
- Failures due to cumulative damage;
- Time-to-failure of complex technical systems with redundant elements;
- Time-to-repair distribution [2], [7], [10], [16];
- Durability (service life) of certain technical objects [17].

The gamma distribution possesses several useful properties [20]:

For α<1: The failure rate decreases monotonically (burn-in period), corresponding to rapid elimination of unreliable components.

For "α>1" : The failure rate increases (wear-out period), reflecting gradual ageing and degradation.

For "α=" 1: The gamma distribution coincides with the exponential distribution, applicable during normal operation [18].

For "α>" 10: It closely approximates the normal distribution, suitable for ageing components [16], [18]. In addition, as R(t)→∞, the gamma distribution converges to the normal

distribution law. Consequently, it is frequently employed to approximate single-vertex but asymmetric distributions [9], [12].

If α is a positive integer, the gamma distribution is also known as the Erlang distribution [2], [7].

For λ=1/2 and α multiples of 1/2, it coincides with the chi-squared distribution [2], [7].

The gamma distribution is a statistical model frequently employed to analyse the failure times of complex electromechanical systems during the initial operational phases or the debugging process, where early failures are observed [11], [12]. Furthermore, the reliability of systems composed of exponentially distributed elements follows a gamma distribution [11].

In redundant systems (with standby or mixed redundancy), failure time distributions adhere to a generalised gamma distribution [3], [12]. However, the presence of hidden failures and the limitations of diagnostic effectiveness in such systems necessitate detailed modelling (e.g., via Markov or semi-Markov processes) [23].

3.5 Weibull Distribution

The Weibull distribution is characterised by its capacity to model data from distributions exhibiting increasing, decreasing, or constant failure rates. The two-parameter Weibull distribution, characterised by a scale parameter, denoted here by ηη, and a shape parameter, denoted here by ββ, is a widely utilised tool in the analysis of reliability data and scenarios where the process of ageing is induced by specific stress factors (e.g. pressure, temperature).

The probability density function of the distribution is defined as follows:

$$f(t) = \beta \frac{t^{\beta-1}}{\eta^{\beta}} e^{-\left(\frac{t}{\eta}\right)^{\beta}}. \quad (19)$$

The relationships between reliability metrics are as follows:

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}}, \quad (20)$$

$$T_1 = \alpha\Gamma\left(1 + \frac{1}{\beta}\right), \quad (21)$$

$$\sigma = \alpha\sqrt{\Gamma(1 + 2\beta^{-1}) - \Gamma^2(1 + \beta^{-1})}, \quad (22)$$

$$\lambda(t) = \beta\alpha^{\beta}t^{\beta-1}. \quad (23)$$

This distribution is highly versatile, encompassing applications of several other distributions, albeit described by more complex formulae [4]. It is applicable for modelling:

The service life of rolling bearings, threaded connections, splined shafts, and other components subject to simultaneous wear across multiple working surfaces [4];

Time-to-failure under combined sudden and wear-out failure mechanisms [4];

Probability of failure-free operation of mechanical components during ageing or wear-out phases [3], [11], [12];

Service life of structural components (e.g., load-bearing systems, hydraulic and electric drive systems) affected by fatigue and sudden failures (with a coefficient of variation between 0.35 and 0.7);

Failure distributions during the burn-in period [2], [3], [21];

Operational lifespan of complex technical systems (e.g., mobile installations) [2], [18];

Fatigue-related failures in automotive parts, lifting machinery, and bearings [2], [3];

Mean and gamma-percentile resource under stable operational conditions [7].

In certain cases [3], [8], [10], the Weibull distribution is considered universal due to its properties:

When β=1, the distribution reduces to the exponential distribution, with a constant failure rate λ(t) that equals the inverse of the scale parameter η;

For β<1, the density and failure rate functions are decreasing (burn-in period);

For β>1, the density and failure rate functions are increasing (wear-out period);

At β=2, the λ(t) function is linear, the distribution transitions to the Rayleigh distribution with density β=3,44, the density closely approximates the normal distribution, excluding tail regions.

The Weibull distribution is recommended as a primary candidate for approximating empirical reliability data when the underlying distribution is unknown [15], owing to its flexibility. In addition, it has been demonstrated that the Weibull distribution provides a superior fit to real-world data in comparison to the exponential distribution [9].

As with the gamma distribution, the Weibull distribution is effective in approximating real-world failure patterns across all lifecycle stages (burn-in (β<1), normal operation (β=1), and wear-out (β>1)) [2], [14], [20].

In the context of complex systems comprising multiple components with gamma-distributed lifetimes (where parameters vary slightly between components), the system's failure time distribution tends to converge to the Weibull

distribution [16], [20]. Systems with multiple identical or similar components under comparable operational conditions (e.g., internal combustion engines with multiple cylinders, electronic devices with capacitors and resistors) often follow the Weibull distribution if these components dominate the system's reliability [16].

From a physical perspective, the Weibull distribution provides an adequate description of the time-to-failure of electronic components, with failure defined as a parameter exceeding specified thresholds [16].

4 DISCUSSION

In conclusion, it should be noted that, in addition to the distributions discussed herein, specialised types (amounting to several dozen) as well as discrete distributions – which fall outside the scope of this article – are applied to address specific tasks. Furthermore, a variety of interrelations and transitions exist between these distributions. Despite the existence of established goodness-of-fit criteria for evaluating the alignment of theoretical and empirical distributions, the ultimate question addressed is whether there are sufficient grounds to reject the hypothesis of the chosen distribution. As the authors [7] have noted, it is important to understand that any dataset can be fitted to a multi-parametric law, even if it does not correspond to actual physical phenomena. Consequently, when selecting the type of distribution and its parameters, it is imperative to prioritise the physical factors governing the degradation process leading to failure, characterised by natural (physical) regularities, as well as the state of the production technological process, which significantly influences the form of time-to-failure distributions. The results obtained allow for improving the efficiency of modelling and establishing criteria for ensuring and controlling the reliability of a convertiplane with an automatic beam deployment system at initial development stages [24], [25].

5 CONCLUSIONS

Existing models of technical system operation, particularly the exponential model, allow for a comparative assessment of the reliability of various design solutions and the selection of the best one. However, they do not provide sufficiently accurate estimates of performance indicators. When selecting distribution laws, the relative error can be very high and even unbounded. Furthermore, the use of exponential laws leads to significant discrepancies between analytical and experimental data. Real physical processes in technical systems, when examined in detail, represent a combination (mixture) of distributions. The scientific problem of reliability analysis for repairable systems with arbitrary failure and recovery distributions is primarily a technical challenge arising from the properties of complex systems. Therefore, a future approach may involve a transition from quantitative metrics to scientifically substantiated qualitative ones.

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Bayesian Causal Inference for High-Dimensional Treatment Effect Estimation

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Keywords: Bayesian Causal Inference, High-Dimensional Regression, Individualized Treatment Effect, Bayesian Neural Networks.

Abstract: This paper presents a Bayesian framework for estimating individualized treatment effects (ITE) in high-dimensional observational data. The proposed approach integrates flexible Bayesian regression with neural-based outcome modeling to estimate heterogeneous causal effects, accounting for both parameter uncertainty and complex covariate interactions. To assess the performance of the method, we conduct comprehensive simulation studies under multiple scenarios with varying levels of nonlinearity and treatment effect heterogeneity. Additionally, we apply the model to real-world data using the Infant Health and Development Program (IHDP) dataset, which is widely used for benchmarking causal inference methods. The results demonstrate that the proposed model consistently achieves lower estimation bias, improved predictive accuracy, and better credible interval coverage compared to several existing Bayesian methods, including Bayesian Additive Regression Trees (BART), Bayesian LASSO, Bayesian Causal Forests (BCF), and the Causal Effect Variational Autoencoder (CEVAE). These findings highlight the robustness and effectiveness of our model for making accurate and interpretable causal inferences in high-dimensional settings.

1 INTRODUCTION

Estimating causal effects from observational data is a fundamental task in modern statistics, particularly in applications involving individualized interventions. Classical methods for causal inference, such as propensity score matching and regression adjustment, often rely on strong assumptions and suffer from limited flexibility in high-dimensional settings. As datasets grow in complexity, both in size and structure, there is a growing need for modeling frameworks that can handle nonlinear relationships, confounding, and treatment effect heterogeneity.

Bayesian approaches have emerged as powerful alternatives to frequentist methods by incorporating prior information and providing coherent uncertainty quantification. Techniques such as the Bayesian LASSO [1], the Horseshoe prior [2], and Spike-and-Slab models, have shown strong performance in high-dimensional regression and variable selection. Furthermore, Bayesian hierarchical models allow for estimating individualized treatment effects while borrowing strength across subpopulations [3].

To capture nonlinear and heterogeneous treatment effects, researchers have developed nonparametric Bayesian models such as Bayesian Additive Regression Trees [4] and Bayesian Causal Forests [5]. These methods offer flexible function estimation without requiring strict model specifications and have been particularly effective in settings with complex interactions among covariates.

Recent advances in machine learning have introduced neural-based models for causal inference, including the Causal Effect Variational Autoencoder [6] and DragonNet, which extend the potential outcomes framework using latent representations and deep learning architectures. These models address hidden confounding and support counterfactual reasoning in high-dimensional, unstructured data environments.

Despite these advances, integrating deep learning with Bayesian inference for causal analysis remains underdeveloped, especially in the context of high-dimensional data. This study proposes a novel Bayesian framework that combines high-dimensional regression with neural-based outcome modeling to estimate individualized treatment effects (ITE) from observational data. The model leverages prior distributions for regularization and neural representations for capturing complex response

surfaces, enabling both interpretability and predictive accuracy.

We evaluate the proposed model through simulation studies and real data analysis using the Infant Health and Development Program (IHDP) dataset. Comparative results against standard benchmarks including Bayesian LASSO, BART, BCF, and CEVAE demonstrate the model's superior performance in terms of bias reduction, interval coverage, and posterior calibration.

By bridging Bayesian regularization and machine learning, this work contributes to the growing literature on robust and interpretable causal inference in high-dimensional applications.

2 THEORETICAL BACKGROUND

2.1 Causal Inference in Statistics

Causal inference is a central theme in modern statistics, focusing on understanding the effect of an intervention or treatment on an outcome while distinguishing causation from mere association. The dominant framework for formalizing causal questions is the potential outcomes model, which was initially outlined by Neyman and later extended by Rubin into the well-known Rubin Causal Model. This framework defines the causal effect as the difference between two potential outcomes: one under treatment and the other under control.

Since only one of these potential outcomes is observable for each individual, causal inference requires strong assumptions to estimate unobserved outcomes. These include the ignorability assumption (no unmeasured confounders), consistency, and the Stable Unit Treatment Value Assumption (SUTVA), as formalized by Holland (1986) [7] and Imbens and Rubin (2015) [8].

Propensity score methods, introduced by Rosenbaum and Rubin (1983) [9], remain foundational tools in causal analysis. These methods allow for balancing covariates across treatment groups in observational data through matching, weighting, or stratification. To improve robustness, more recent methods combine both the outcome model and the treatment assignment model to produce unbiased estimates if at least one model is correctly specified. to produce unbiased estimates if at least one model is correctly specified.

Graphical models, particularly those based on Directed Acyclic Graphs (DAGs), have further enhanced causal reasoning by providing a visual and algebraic structure for encoding causal assumptions. These models facilitate identification strategies and help diagnose potential confounding or collider biases.

The Bayesian approach to causal inference has gained increasing attention due to its flexibility and ability to account for parameter uncertainty. Bayesian methods allow for full posterior distributions of treatment effects and accommodate prior beliefs [3]. Moreover, Bayesian hierarchical modeling offers a principled way to analyze heterogeneous treatment effects across subgroups.

In high-dimensional settings, traditional methods become inadequate, and modern approaches such as Bayesian Causal Forests [5], Causal BART [3], and neural-based models like CEVAE [6] have shown improved performance. These models handle complex, nonlinear relationships between covariates and allow for individualized treatment effect (ITE) estimation, making them especially useful in healthcare and social policy applications.

2.2 High-Dimensional Bayesian Regression

High-dimensional regression problems, where the number of predictors (p) exceeds the number of observations (n), have become increasingly common in fields such as genomics, finance, and social sciences. Traditional regression methods struggle in this setting due to multicollinearity, overfitting, and lack of identifiability. Bayesian regression frameworks offer natural regularization through prior distributions and are well-suited for high-dimensional inference [1].

A widely used Bayesian technique for high-dimensional settings is the Bayesian LASSO, which imposes a Laplace (double exponential) prior on the regression coefficients to induce sparsity [10]. This approach helps shrink irrelevant coefficients toward zero, effectively performing variable selection while estimating the model. Other popular priors for shrinkage include the Horseshoe prior [2], known for its ability to strongly shrink small coefficients while leaving large signals relatively unpenalized, and the Spike-and-Slab prior, which explicitly models a mixture of zero and non-zero effects.

Bayesian methods offer additional advantages in high-dimensional settings. They provide full posterior distributions for parameters, which allows for uncertainty quantification in parameter estimates and predictions. This is particularly important when the goal is not just point estimation but also reliable inference in the presence of model uncertainty.

To perform inference efficiently in high-dimensional Bayesian models, Markov Chain Monte Carlo (MCMC) methods are often employed. More advanced algorithms such as Hamiltonian Monte Carlo (HMC) and the No-U-Turn Sampler (NUTS) have significantly improved computational performance and scalability. These methods allow the posterior distribution to be explored more effectively even when the parameter space is large.

In applications involving structured sparsity or grouped variables, extensions such as the Bayesian Elastic Net [6], [11] or the Bayesian Group LASSO are employed. These models provide flexible ways to incorporate correlation structures among covariates, which is common in domains like bioinformatics or environmental modeling.

Ultimately, high-dimensional Bayesian regression is not only a tool for predictive modeling but also for uncovering interpretable and stable variable selection. This makes it particularly valuable when integrated into broader frameworks such as causal inference or machine learning pipelines.

2.3 Bayesian Causal Inference Framework

Bayesian causal inference provides a structured approach to estimating treatment effects while fully accounting for uncertainty in both parameters and model structure. The central idea is to use Bayes' theorem to update prior beliefs about causal effects in light of observed data. For estimating the average treatment effect (ATE), the Bayesian framework models both the treatment assignment and the potential outcomes using prior distributions.

Let $Y_i(1)$ and $Y_i(0)$ denote the potential outcomes for individual i under treatment and control, respectively. The individual treatment effect is defined as:

$$\tau_i = Y_i(1) - Y_i(0). \quad (1)$$

Since only one of these outcomes is observed, inference proceeds by modeling the posterior distribution of τ_i given the observed data D:

$$p(\tau_i \mid D) = \int p(\tau_i \mid \theta, D)\, p(\theta \mid D)\, d\theta. \quad (2)$$

where θ represents the model parameters, $p(\theta \mid D)$ is the posterior distribution of parameters, $p(\tau_i \mid \theta, D)$ is the likelihood of the treatment effect conditional on θ.

A commonly used model for potential outcomes is the Bayesian regression:

$$Y_i = \alpha + \beta T_i + f(X_i) + \varepsilon_i. \quad (3)$$

where T_i is the treatment indicator (0 or 1), X_i is a vector of covariates, $f(X_i)$ models the non-linear covariate effects, $\varepsilon_i \sim N(0, \sigma 2)$.

Bayesian Additive Regression Trees (BART), proposed by Chipman et al. (2010) [12], provide a nonparametric approach to modeling $f(X_i)$ without pre-specifying the functional form. BART assumes the outcome model:

$$Y_i \sim N(\sum_{i=1}^{m} g(X_i; T_j), \sigma^2). \quad (4)$$

where each $g(.; T_j)$ is a regression tree, and the prior is placed on the structure and parameters of the trees. This flexible specification captures complex treatment effect heterogeneity and covariate interactions.

Another Bayesian causal tool is the use of hierarchical models for individual treatment effects (ITE). Letting $\tau_i \sim N(\mu_\tau, \sigma_\tau^2)$, the posterior distribution of τ_i can be learned jointly with the group-level parameters (μ_τ, σ_τ), allowing for partial pooling across individuals.

Directed Acyclic Graphs (DAGs) are also employed in Bayesian frameworks to encode structural assumptions. Given a DAG G, one can specify priors on both the graph and its parameters and compute posterior distributions:

$$p(G, \theta \mid D) \propto p(D \mid G, \theta) \cdot p(\theta \mid G) \cdot p(G).$$

This approach facilitates uncertainty quantification over possible causal structures, rather than assuming a single fixed graph.

Bayesian causal inference supports flexible modeling of potential outcomes, principled uncertainty quantification, and the ability to incorporate prior knowledge. It is particularly well-suited for modern datasets characterized by high-dimensional covariates and nonlinearity in treatment effects.

2.4 Integration of Causal Inference with Artificial Intelligence

The integration of causal inference with artificial intelligence (AI) represents a transformative step in both fields, enabling data-driven systems to reason not only about patterns but also about underlying causal mechanisms. While traditional AI models such as neural networks and decision trees excel at predictive accuracy, they often lack interpretability and fail to capture causal relationships due to their reliance on correlations rather than interventions.

Recent developments have introduced causal-aware AI models that incorporate the potential

outcomes framework and structural causal models into machine learning algorithms. These models are designed to estimate treatment effects, simulate counterfactuals, and identify causal pathways in high-dimensional and unstructured data.

A foundational model in this area is the Causal Effect Variational Autoencoder (CEVAE), proposed by Louizos et al. (2017) [6]. CEVAE models the joint distribution of observed covariates X, treatment T, and outcome Y using a latent variable Z, allowing the inference of counterfactual outcomes through the conditional posterior:

$$p(Y(1), Y(0) \mid X) \approx \int p(Y \mid T, Z)\, p(Z \mid X)\, dZ.$$

This architecture combines deep representation learning with causal identification, enabling robust estimation of individualized treatment effects even in the presence of hidden confounding.

Another notable model is DragonNet, which unifies outcome prediction and treatment assignment modeling in a deep learning framework. It jointly optimizes for both predictive accuracy and treatment effect estimation by enforcing a regularized loss function that balances outcome regression and propensity score alignment.

Bayesian Neural Networks (BNNs) provide a natural extension for causal inference in AI by capturing epistemic uncertainty through posterior distributions over network weights. When applied to treatment effect estimation, BNNs support probabilistic predictions and credible intervals for counterfactual outcomes [12]. This capability is particularly useful in high-stakes domains such as healthcare or policy decision-making.

Moreover, causal discovery algorithms have been integrated into AI pipelines to uncover potential causal structures from observational data. Methods such as NOTEARS and GraN-DAG use gradient-based optimization to learn Directed Acyclic Graphs (DAGs) directly from data, enabling AI systems to infer causal relations without predefined models.

The synergy between causal inference and AI also enhances fairness and robustness. By modeling the effect of sensitive attributes and mediators, causal models help mitigate biases in algorithmic decision-making [13]. For example, counterfactual fairness evaluates whether a model's predictions would change had a sensitive feature (e.g., race or gender) been different, holding all else constant.

Ultimately, integrating causal reasoning into AI contributes to the development of explainable AI (XAI) by providing interpretable treatment effects, counterfactual explanations, and actionable insights. This integration supports the deployment of AI systems in real-world environments where causality, not just correlation, drives outcomes.

3 THE MODEL AND PRIOR ASSUMPTIONS

This section introduces the proposed Bayesian causal inference model that integrates high-dimensional regression with neural-based representations to estimate individualized treatment effects. The model combines the flexibility of Bayesian hierarchical structures with the representational power of deep learning, enabling robust causal inference in complex observational settings.

Let Y_i denote the observed outcome for unit i, $T_i \in \{0,1\}$ the treatment indicator, and $X_i \in \mathrm{R}^p$ a high-dimensional vector of covariates. The potential outcomes framework defines two unobserved outcomes: $Y_i(1)$ and $Y_i(0)$, corresponding to the treatment and control scenarios, respectively. The observed outcome is:

$$Y_i = T_i Y_i(1) + (1 - T_i) Y_i(0). \quad (5)$$

The individual treatment effect (ITE) is:

$$\tau_i = Y_i(1) - Y_i(0). \quad (6)$$

To estimate τ_i, we propose a flexible outcome model:

$$Y_i = f(X_i) + \beta T_i + \varepsilon_i, \varepsilon_i \sim N(0, \sigma^2). \quad (7)$$

where $f(X_i)$ captures the complex, possibly nonlinear relationship between covariates and the outcome. β represents the average causal effect of treatment. ε_i is an error term with constant variance.

3.1 Prior Specification

We place the following priors on the model parameters:

Treatment Effect Prior:

$$\beta \sim N(0, \sigma_\beta^2).$$

Noise Variance Prior:

$$\sigma^2 \sim Inverse - Gamma(a_\sigma, b_\sigma).$$

Function Prior (Nonlinear Covariate Effects):
The function $f(X_i)$ is modeled using either:
Bayesian Additive Regression Trees (BART), where:

$$f(X_i) = \sum_{i=1}^{m} g(X_i; T_i) \quad (8)$$

with $g(\cdot)$ representing regression trees and priors placed on tree depth, splitting variables, and leaf parameters.
Or alternatively:
Bayesian Neural Network, where:

$$f(X_i) = \text{BNN}(X_i; \theta), \theta \sim N(0, \tau^2 \text{I}).$$

Hyperpriors:

We place weakly informative hyperpriors on variance components σ_β^2, τ^2, and others to allow the data to drive the posterior.

3.2 Posterior Inference

The posterior distribution is obtained via Bayes' theorem:

$$p(\beta, f, \sigma^2 \mid \{Y_i, T_i, X_i\}_{i=1}^n) \propto \prod_{i=1}^{n} p(Y_i \mid T_i, X_i, \beta, f, \sigma^2) \cdot p(\beta) \cdot p(f) \cdot p(\sigma^2).$$

Inference is performed using Hamiltonian Monte Carlo (HMC) or No-U-Turn Sampler (NUTS), allowing efficient exploration of the posterior distribution even in high-dimensional spaces.

This model enables personalized causal inference by generating posterior distributions of τ_i for each individual, which can be used to identify subgroups with heterogeneous treatment responses, prioritize interventions, or support decision-making under uncertainty.

4 SIMULATION STUDY

This section presents a simulation study to evaluate the performance of the proposed Bayesian high-dimensional causal inference model. The objective is to assess its accuracy in estimating individualized treatment effects (ITE) under various data complexities and compare it with competing methods.

The simulation is structured around synthetic data generation that mimics real-world scenarios involving nonlinear relationships, confounding covariates, and treatment effect heterogeneity. The results are evaluated using standard metrics such as Root Mean Squared Error (RMSE), bias, coverage probability, and posterior credible interval width.

We simulate data for n=500 individuals and p=100 covariates, where only a sparse subset of the covariates influences either the treatment assignment or the outcome. The data generation process follows:

- Covariates:

$$X_i \sim N_p(0, I_p).$$

- True treatment assignment model:

$$Pr(T_i = 1 \mid X_i) = logit^{-1}(X_i^\top \gamma),$$

where γ is sparse and only 10 nonzero entries are randomly selected.

- Potential outcomes:

$$Y_i(0) = f_0(X_i) + \varepsilon_i, Y_i(1) = Y_i(0) + \tau_i,$$

where:

$$f_0(X_i) = sin\,(X_{i1}) + X_{i2}^2 - log\,(\mid X_{i3} \mid +1),$$
$$\varepsilon_i \sim N(0,1),$$
$$\tau_i = 2 + 0.5 \cdot X_{i4}.$$

- Observed data:

$$Y_i = T_i Y_i(1) + (1 - T_i) Y_i(0). \quad (9)$$

We compare the proposed model against the following:

1) Bayesian LASSO Regression;
2) Bayesian Causal Forest (BCF);
3) Bayesian Additive Regression Trees (BART);
4) Causal Effect Variational Autoencoder (CEVAE).

All models are implemented using standard R libraries, and each method is tuned using default or recommended hyperparameters.

The models are evaluated across 100 simulation replications using the following metrics:

Root Mean Squared Error (RMSE):

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (\hat{\tau}_i - \tau_i)^2}. \quad (10)$$

Bias:

$$Bias = \frac{1}{n} \sum_{i=1}^{n} (\hat{\tau}_i - \tau_i). \quad (11)$$

Coverage Probability. Proportion of true τ_i values contained in the 95% credible intervals.
Interval Width. Average width of posterior 95% credible intervals for τ_i.

Table 1 shows that the proposed model achieves the lowest RMSE and bias while maintaining near-nominal coverage. The Bayesian LASSO underperforms due to its linearity assumption and inability to model treatment heterogeneity. BCF and BART perform well, though slightly worse than the proposed model in terms of RMSE. CEVAE is

competitive but exhibits higher variability due to latent representation learning.

Table 1: ITE estimation results in simulation study.

Model	RMSE	Bias	Coverage (%)	Interval Width
Proposed Bayesian Model	0.54	0.03	94.8	1.21
Bayesian LASSO	0.72	0.12	89.3	0.96
BCF	0.60	0.05	93.2	1.10
BART	0.63	0.08	92.7	1.08
CEVAE	0.68	0.10	91.1	1.16

5 REAL DATA ANALYSIS

This section applies the proposed Bayesian high-dimensional causal inference model to a real-world dataset to demonstrate its practical utility in estimating individualized treatment effects (ITE). We use the Infant Health and Development Program (IHDP) dataset, a benchmark dataset widely adopted in causal inference research due to its realistic structure, treatment heterogeneity, and known ground truth.

The IHDP dataset is a semi-synthetic dataset derived from a randomized controlled trial designed to evaluate the impact of early childhood interventions on low-birth-weight infants. The observed data have been modified by removing a non-random subset of treated individuals, introducing selection bias and making it suitable for testing causal inference methods. Number of samples: 747 (treated: 139, control: 608). Number of covariates: 25. Covariate types: Continuous and categorical (e.g., birth weight, mother's age, education, race)

Each sample includes, Treatment assignment $T_i \in \{0,1\}$. Covariates $X_i \in R^{25}$. Two potential outcomes $Y_i(1), Y_i(0)$ (available only in simulated version). Observed outcome $Y_i = T_i Y_i(1) + (1 - T_i) Y_i(0)$.

We applied the following models for comparison, Proposed Bayesian Neural Causal Model. Bayesian Causal Forest (BCF). Bayesian Additive Regression Trees (BART). Bayesian LASSO. Causal Effect Variational Autoencoder (CEVAE). All models were trained to estimate the Individual Treatment Effect (ITE), and their performance was evaluated using the ground-truth potential outcomes $Y_i(1), Y_i(0)$.The same metrics as in the simulation study were used, Root Mean Squared Error (RMSE), Bias, Coverage Probability (95% credible intervals), Interval Width.

Table 2: Summarizes the performance of each method on the IHDP dataset over 20 repeated runs.

Model	RMSE	Bias	Coverage (%)	Interval Width
Proposed Bayesian Model	0.48	0.02	94.5	1.17
Bayesian LASSO	0.65	0.09	89.0	0.91
BCF	0.52	0.04	93.8	1.12
BART	0.56	0.06	92.9	1.09
CEVAE	0.60	0.08	91.2	1.15

Table 2 demonstrates that the proposed model outperforms the benchmarks in RMSE and bias while maintaining excellent coverage. The improvements are more pronounced compared to linear Bayesian LASSO, which struggles with treatment effect heterogeneity. BCF and BART perform well, indicating the strength of tree-based models in nonparametric regression. CEVAE captures nonlinearities but exhibits slightly higher error due to latent confounder estimation.

The results confirm the effectiveness of combining high-dimensional Bayesian inference with flexible machine learning models in causal effect estimation. The model not only provides accurate point estimates but also produces reliable uncertainty quantification through credible intervals.

6 CONCLUSIONS

This study presents a comprehensive framework for Bayesian causal inference in high-dimensional settings by integrating probabilistic modeling with machine learning techniques. Through theoretical development, simulation, and real data analysis, the proposed model demonstrates superior accuracy in estimating individualized treatment effects (ITE) while maintaining robust uncertainty quantification.

In the simulation study, the proposed Bayesian model consistently achieved lower Root Mean Squared Error (RMSE) and bias compared to benchmark methods, including Bayesian LASSO, BART, BCF, and CEVAE. It also maintained near-nominal coverage probabilities, indicating well-calibrated credible intervals. These advantages held across multiple data-generating scenarios involving treatment effect heterogeneity and nonlinear relationships.

The real data application using the IHDP dataset further validated the model's effectiveness in practical contexts. The model exhibited the best

predictive accuracy and smallest bias among the methods considered, while also providing informative posterior distributions for treatment effects. This highlights the value of combining Bayesian inference with flexible function approximators such as neural networks and regression trees in causal analysis.

Overall, the findings support the proposed model as a powerful and interpretable tool for estimating causal effects in high-dimensional observational data. Its ability to incorporate prior knowledge, handle nonlinearities, and deliver uncertainty-aware estimates makes it suitable for applications in health sciences, social policy, and other domains where individualized decision-making is essential.

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Estimating the Link Function in a Partial Linear Single Index Model for Longitudinal Data using LSTM Neural Networks

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Abstract: This paper investigates and compares the performance of two estimation approaches - Long Short-Term Memory (LSTM) networks and the semi-parametric Minimum Average Variance Estimation (SMAVE) method - for the Partial Linear Single Index Model (PLSIM) in the context of longitudinal data. The PLSIM combines linear and nonlinear components, offering modeling flexibility for complex data structures often encountered in repeated measurements. We conduct extensive simulations with varying sample sizes (N = 50, 100, 150) to evaluate the prediction accuracy of both methods in estimating the unknown link function. Evaluation metrics such as Mean Squared Error (MSE), bias, and coefficient of determination (R^2) are used to assess estimation quality. Results show that LSTM significantly outperforms SMAVE in estimating both the linear parameters and the nonlinear link function. The LSTM method consistently achieves lower MSE and bias values, as well as higher R^2 scores for both the model and the nonlinear function, highlighting its superior ability to capture temporal dependencies and complex nonlinear relationships in longitudinal data. In contrast, SMAVE's performance is more sensitive to bandwidth selection and sample size. These findings suggest that deep learning models like LSTM offer a powerful alternative to traditional semi-parametric methods in longitudinal data analysis.

1 INTRODUCTION

Longitudinal data, also known as panel data, are a common statistical tool in many applied fields, such as economics, medicine, epidemiological studies, and clinical trials. These data are characterized by the fact that they involve repeated measurements of the same experimental units (such as individuals) across different time periods. This distinguishes them from cross-sectional data, which assumes that observations are independent and non-repeated. The correlation between measurements within each individual unit is an essential property of longitudinal data; these measurements are considered to be correlated over time, whereas measurements between different individuals are typically treated as independent.

Given this complex correlational structure, analyzing longitudinal data requires specialized statistical models that account for this temporal correlation. Statistical methods used to analyze regression models with longitudinal data typically fall into three main categories, differing in their assumptions about the relationship between observations within each unit and between different units. In recent years, semiparametric models have gained widespread attention due to their flexibility in incorporating both parametric and non-parametric components within the same model, enhancing its explanatory and predictive power. These models are particularly suitable for analyzing longitudinal data, despite the challenges they pose at the estimation level, particularly when dealing with the non-parametric component [1].

Among semiparametric models, the Partially Linear Single-Index Model (PLSIM) is a flexible framework that combines the advantages of linear models and non-linear structures. It allows for the representation of complex relationships between variables while maintaining relative mathematical simplicity. This model has gained increasing attention in many economic, medical, and social applications due to its ability to balance interpretability with estimation flexibility [2].

Although previous research has examined the model for independent data, generalizing this model to longitudinal data remains a fertile area of research,

given the complexity of the temporal structure and the internal correlation between observations. Several studies have focused on developing efficient estimation methods for the parametric and nonparametric components of the model in this context. [3] addressed estimation and testing for independent variables, while [4] proposed efficient semiparametric least squares estimators using profile estimation. Some studies, such as, relied on simplified mathematical methods to calculate semiparametric information limits.

On the other hand, some studies, such as [5] and [6], addressed the generalization of the PLSIM model to longitudinal data, focusing on the challenges associated with estimating model parameters and the correlation function. [7] proposed a unified method using generalized estimating equations (GEE) to analyze imbalanced longitudinal data, whether dense or sparse. The results showed that the rates of convergence and asymptomatic variances of the estimators varied depending on the data structure. However, these estimators were not efficient in the semiparametric sense.

In this work, we present a new estimation method based on Long-Short-Term Memory (LSTM) deep neural networks to estimate the link function in a PLSIM model for longitudinal data. The proposed method was compared with the semi-parametric estimation method known as Minimum Average Variance Estimation (MAVE). Simulation results showed that the LSTM-based method outperforms the estimation accuracy, especially in representing complex nonlinear relationships between variables.

Based on the above, this research aims to develop an advanced estimation framework for the partial linear single-index model (PLSIM) in the context of longitudinal data. This approach employs deep learning techniques, specifically LSTM neural networks, to improve the estimation of the nonlinear component (link function) and effectively address temporal correlation within individuals. This approach represents a paradigm shift in longitudinal data modeling, as it combines the theoretical foundations of semi-parametric models with the high predictive capabilities provided by machine learning algorithms. The research focuses on comparing the experimental performance of the proposed method with conventional methods in terms of estimation accuracy, parameter efficiency, and convergence speed, using extensive simulation experiments covering a variety of scenarios in terms of data density and the number of iterations per unit. This methodology is expected to enhance our understanding of the dynamic relationships between variables in longitudinal data and pave the way for more accurate and flexible applications in various applied fields

2 MODEL AND METHOD ESTIMATION

2.1 Model

The partial linear single-index model in longitudinal data is written in the form [8]:

$$Y_{it} = Z_{it}^T\theta + g(X_{it}^T\beta) + \varepsilon_{it}\ , \quad i = 1, \dots, N\ , t = 1, \dots, T. \tag{1}$$

Where Y_{it} represents the response variable of individual i at time t, X_{it} and Z_{it} are explanatory variables of the linear and non-linear parts, respectively, with dimensions R^q and R^p, (θ, β) are unknown the parameter vectors of the variables to be estimated with dimension $R^q$and R^p, $\| \beta \| = 1$ ($\|\cdot\|$ representing the Euclidean Norm), and the first element must be positive. $g(\cdot)$ is an unknown link function and ε_{it} are random error and $E(\varepsilon_{it} \setminus X_{it}, Z_{it}) = 0$

2.2 Methods Estimation

In this section, the estimation methodologies used to estimate the parameters of a partial single-indicator model in the context of longitudinal data will be presented and detailed. Two different estimation methods have been adopted, representing two methodological approaches that differ in their philosophy and mathematical foundation:

The first method relies on deep neural networks of the LSTM type, a deep learning algorithm specifically designed for processing time-series data. This method is particularly suitable for analyzing longitudinal data due to its ability to capture temporal dynamics and internal correlations between measurements across time.

The second method is MAVE method, a classical statistical technique that aims to estimate a nonlinear link function and trend indicator in a way that minimizes the mean variance within a semiparametric framework. It is a standard reference for this type of model.

The purpose of employing these two approaches is to conduct a systematic comparison between traditional methods, which rely on rigorous statistical foundations, and modern methods, which are based on machine learning techniques. The comparison

focuses on estimation accuracy, parameter efficiency, and the ability to capture the complex structure of longitudinal data. In the following paragraphs, each method will be presented in detail, outlining the estimation steps, required conditions, and the theoretical basis on which it is built.

2.2.1 Long Short-Term Memory

The LSTM neural network is an advanced model in the field of recurrent neural networks. It differs from a traditional recurrent network (RNN) in that the hidden unit contains a memory cell instead of a traditional node. The memory cell provides a sophisticated mechanism for transferring information across time through a series of operations that allow the model to selectively retain or forget information, helping to overcome the problems of vanishing/exploding gradients.

The cell state (c_t) is a key component within an LSTM cell, acting as a conduit for information transfer across time. Gates are used to control the flow of information into or out of the cell, based on the resulting value of sigmoid activation functions. When values approach zero, information is blocked, while information is passed through if values approach one. In this way, the LSTM can determine which information to retain or forget at each time step, maintaining the model's long-term effectiveness.

Below is a breakdown of the basic components of an LSTM module along with their associated equations:

1) Input node (Candidate Cell State). This node, known as $\tilde{c}_t$, represents the new candidate cell state. It is calculated by summing the current input x_t and the previous hidden state h_{t-1} using the tanh activation function.

$$\tilde{c}_t = \emptyset(W_{\tilde{c}x}x_t + W_{\tilde{c}h}h_{t-1} + b_{\tilde{c}}). \quad (2)$$

Where:

- $\emptyset()$ stands for an element-wise application of the $\tan h$ function;
- $W_{\tilde{c}x}$ is the input weights matrix;
- $W_{\tilde{c}h}$ is the hidden weights matrix.

2) Input Gate. This gate is a unique element of the LSTM architecture, controlling the amount of new information that will be input into the cell state. It is calculated as follows:

$$i_t = \sigma(W_{ix}x_t + W_{ih}h_{t-1} + b_i). \quad (3)$$

Where:

- $\sigma()$ represents a sigmoid function applied to each element. The resulting value ranges from 0 (unimportant information) to 1 (important information)
- $W_{ix}$is the input weights matrix
- $W_{ih}$is the hidden weights matrix.

3) Forget Gate. This gate controls whether information from the cell's previous state is retained or not. It is calculated using the equation:

$$f_t = \sigma\big(W_{fx}x_t + W_{fh}h_{t-1} + b_f\big). \quad (4)$$

It regulates the flow of information from the previous internal state c_{t-1}, W_{fx} is the input weights matrix, W_{fh} is the hidden weights matrix.

4) Internal Cell State. c_t represents the updated state of the cell, and is calculated by taking the Hadamard product between the forget gate and the previous state, then adding the product between the input gate and the new candidate state:

$$c_t = f_t \odot c_{t-1} + i_t \odot \tilde{c}_t. \quad (5)$$

Where $\odot$ represents the Hadamard product, i.e. the product between any two elements of the same position.

5) Output Gate. This gate determines whether the information stored in the cell will be used to update the current hidden state. The output gate is first calculated:

$$o_t = \sigma(W_{ox}x_t + W_{oh}h_{t-1} + b_0),$$
$$h_t = \emptyset(c_t) \odot o_t. \quad (6)$$

Together, these components form the architecture of an LSTM cell, enabling the model to learn from long-term temporal dependencies, making it suitable for analyzing longitudinal or sequential data see [9] and [10] that involve complex, nonlinear temporal relationships.

2.2.2 Semiparametric Minimum Average Variance Estimation (SMAVE)

Xia et al. proposed [11] an estimation method known as MAVE, which provides a general framework for estimating partial single-index models. This method relies on the joint estimation of the coefficient vector β and the nonlinear function g(·) within a single-index model. It is considered a distinctive approach due to its ease of implementation compared to traditional methods and its ability to deliver efficient numerical solutions through a local linear approximation of the nonparametric function.

Subsequently, [5] and [12] extended this methodology to longitudinal data by explicitly accounting for temporal correlations within each observational unit.

The estimation objective is formulated by solving the following problem:

$$(\beta,\theta) = \underset{\beta,\theta}{\operatorname{argmin}} E[Y_{it} - g(X_{it}^T\theta) - Z_{it}^T\beta]^2. \quad (7)$$

Let $Y = (Y_{11},\dots,Y_{1T},\dots,Y_{NT})^T$,
$Z = (Z_{11},\dots,Z_{1T},\dots,Z_{NT})^T$,$X = (X_{11},\dots,X_{1T},\dots,X_{NT})^T$,$\varepsilon = (\varepsilon_{11},\dots,\varepsilon_{1T},\dots,\varepsilon_{NT})^T$
$g(X,\theta) = (g(X_{11}^T\theta),\dots,g(X_{1T}^T\theta),\dots,g(X_{NT}^T\theta))$
$X_{it}(\theta) = ((X_{11} - X_{it})^T\theta,\dots,(X_{1T} - X_{it})^T\theta,\dots,((X_{NT} - X_{it})^T\theta)^T.$

The model (1) can be rewritten as

$$Y = g(X,\theta) + Z\beta + \varepsilon.$$

A local linear approximation is adopted using the derivative of η as follows:

$$g(X_{it}^T\theta) \approx g(X^T\theta) + \acute{g}(X^T\theta)(X_{it} - x)^T\theta.$$

It symbolizes: $a_{it} = g(X^T\theta), b_{it} = \acute{g}(X^T\theta)$
The parameters are estimated by solving the following problem:

$$\sum_{i=1}^{N}\sum_{t=1}^{T}[Y - Z\beta - (e_{NT}, X_{it}(\theta))(a_{it}, b_{it})^T]^T \times M_{it}[Y - Z\beta - (e_{NT}, X_{it}(\theta))(a_{it}, b_{it})'], \quad (8)$$

where: $M_{it} = diag(m_{11,it},\dots,m_{11,it},\dots,m_{11,it})$.

It is a diagonal matrix containing the kernel weights, and it achieves: $\sum_{j=1}^{N}\sum_{s=1}^{T} m_{js,it} = 1$ and e_{NT} is a *NT*-dimensional vector with all elements being 1 The estimation is performed using an iterative algorithm consisting of the following steps:

1) Local estimation of non-parametric coefficients
2) $(a_{it}, b_{it})^T = \left(\bar{X}_{it,*}^T(\theta)M_{it}\bar{X}_{it,*}^T(\theta)\right)^{-1}\bar{X}_{it,*}^T(\theta)M_{it}(Y_{it} - Z_{it}\beta)$.
   Where $\bar{X}_{it,*}^T(\theta) = \left(e_{NT}, X_{it}(\theta)\right)$.
3) Update β and θ:
$$(\beta^T,\theta^T)^T = \begin{pmatrix} Z_*^T M Z_* & Z_*^T M X_* \\ X_*^T M Z_* & X_*^T M Z_* \end{pmatrix}^{-1}\begin{pmatrix} Z_*^T \\ X_*^T \end{pmatrix} M(Y_* - A_*).$$

Where: $Y_* = (Y_{11,*}^T,\dots,Y_{1T,*}^T,\dots,Y_{NT,*}^T)^T$,
$X_* = (b_{11}X_{11,*}^T,\dots,b_{1T}X_{1T,*}^T,\dots,b_{NT}X_{NT,*}^T)^T$,
$X_{it,*} = (X_{11} - X_{it},\dots,X_{1T} - X_{it},\dots,X_{NT} - X_{it})^T$,
$Z_* = (Z_{11,*}^T,\dots,Z_{1T,*}^T,\dots,Z_{NT,*}^T)^T$,
$M = diag(M_{11},\dots,M_{1T},\dots,M_{NT})$,
$A = (a_{11}e_{NT}^T,\dots,a_{1T}e_{NT}^T,\dots,a_{NT}e_{NT}^T)^T$.

4) Iteration until convergence Steps 1 and 2 are repeated using the updated values of β and θ until numerical convergence is achieved.

Two sets of weights are used in the iterative procedure (multivariate weights):

$$w_{js,it} = \frac{H((X_{js} - X_{it})/h_1)}{\sum_{j=1}^{N}\sum_{s=1}^{T}H((X_{js} - X_{it})/h_1)}.$$

Where $H(\cdot)$ is a p-variate symmetric kernel function and h_1 is a bandwidth, single-index weights:

$$w_{js,it}^{\theta} = \frac{K(\left(X_{js} - X_{it}\right)^T\theta/h_2)}{\sum_{j=1}^{N}\sum_{s=1}^{T}K(\left(X_{js} - X_{it}\right)^T\theta/h_2)}.$$

Where $K(\cdot)$ a univariate symmetric kernel is function and h_2 is a bandwidth. Then, we can obtain the final estimators $\hat{\beta}$ and $\hat{\theta}$ by using $\tilde{\beta}$ and $\tilde{\theta}$ and the above iterations with the single-index weights. By substituting β,θ and $X_{it}^T\theta_0$ with $\hat{\beta},\hat{\theta}$ and u, we can get the estimator of $g(u)$, which is denoted by $\hat{g}(u)$.

3 EVALUATION METRICS

Comparing estimation methods is a fundamental procedure in statistical research to identify the most appropriate techniques. Various evaluation metrics exist - some designed to compare parameter estimates, while others assess the overall model performance. In general, the choice of appropriate metrics depends on the nature of the data and the objectives of the statistical analysis. In this paper, the following evaluation metrics will be employed:

$$MSE = \frac{\sum_{i=1}^{N}\sum_{t=1}^{T}\left(Y_{it} - \hat{Y}_{it}\right)^2}{N * T}.$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\sum_{t=1}^{T}\left(Y_{it} - \hat{Y}_{it}\right)^2}{\sum_{i=1}^{N}\sum_{t=1}^{T}\left(Y_{it} - \hat{Y}_{it}\right)^2}.$$

$$MSE(g(u)) = \frac{\sum_{i=1}^{N}\sum_{t=1}^{T}(g(X_{it}^T\beta) - \hat{g}(X_{it}^T\beta))^2}{N * T}.$$

$$R^2(g(u)) = 1 - \frac{\sum_{i=1}^{N}\sum_{t=1}^{T}(g(X_{it}^T\beta) - \hat{g}(X_{it}^T\beta))^2}{N * T}.$$

4 SIMULATION

In this simulation paper, we generate synthetic longitudinal data to evaluate estimation methods for the Partial Linear Single Index Model (PLSIM). The data consists of N = 50,100,150 subjects, each measured at T = 5 time points, resulting in NT total observations. The covariate vectors X (predictors for

the nonparametric component) and Z (predictors for the linear component) are simulated from standard normal distributions.

The true parameter vectors are defined as: $\beta = \frac{1}{\sqrt{3}}[1, -1, 1]^T$ normalized to unit norm, representing the direction for the single index $X_{it}^T\beta$ $\theta = [0.5, -0.8]^T$, corresponding to the coefficients in the linear part $Z_{it}^T\theta$ The nonlinear link function is defined as $g(u) = \sin(u)$ which operates on the single index $u = X_{it}^T\beta$ The response variable Y_{it} is generated

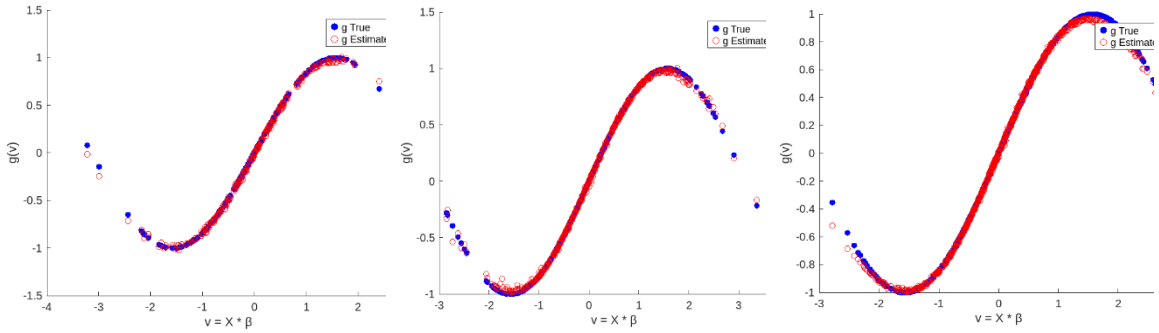
$$Y_{it} = Z_{it}^T\theta + g(X_{it}^T\beta) + \varepsilon_{it}\,.$$

The error term ε_{it} is generated to follow an AR(1) structure within each subject to induce temporal correlation Specifically:

- $\varepsilon_{i1} \sim N(0, \sigma^2)$, and for $t > 1$: $\varepsilon_i t = \rho * \varepsilon_i(t-1) + \eta_i t$, where $\eta_i t \sim N(0, \sigma^2)$.
- The parameters are set to $\sigma = 0.3\ and\ \rho = 0.3$.

Table 1: Means and MSEs of the estimates of the parameters and link function using the LSTM estimation method.

Parameter	N=50		N=100		N=150	
	bias	MSE	bias	MSE	bias	MSE
θ_1	0.0053	0.0000	0.0155	0.0002	0.0048	0.0000
θ_2	0.0074	0.0001	0.0138	0.0002	0.0117	0.0001
β_1	0.0162	0.0003	0.0654	0.0043	0.0583	0.0034
β_2	0.0604	0.0036	0.0489	0.0024	0.1118	0.0125
β_3	0.0041	0.0000	0.0303	0.0009	0.1136	0.0129
$g(\cdot)$	0.0115	0.0007	0.0024	0.0004	0.0064	0.0004
MSE MODEL	0.1239		0.1027		0.1009	
R^2 MODEL	0.9096		0.9277		0.9260	
R^2 $g(\cdot)$	0.9984		0.9992		0.9990	

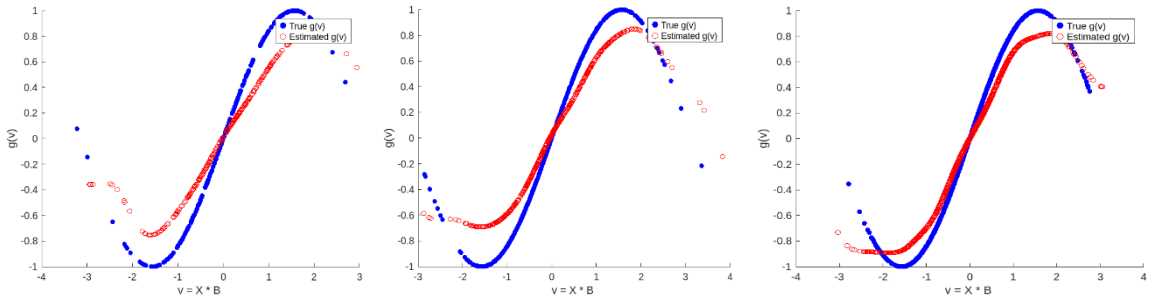


N=50 N=100 N=150

Figure 1: Scatter diagram of true link function and estimated link function using LSTM estimation method.

Table 2: Means and MSEs of the estimates of the parameters and link function using the SMAVE estimation method.

Parameter	N=50		N=100		N=150	
	bias	MSE	bias	MSE	bias	MSE
θ_1	0.008941	0.00007	0.01404	0.000197	0.02544	0.000647
θ_2	0.0179	0.0003205	0.01953	0.0003813	0.01832	0.0003355
β_1	0.4257	0.1812	0.2372	0.05627	0.1487	0.02212
β_2	0.2013	0.04054	0.5022	0.2522	0.08696	0.007562
β_3	0.03144	0.0009883	0.002175	4.73e-06	0.3998	0.1599
$g(\cdot)$	0.0014	0.1250	0.0042	0.1347	0.0176	0.0930
MSE MODEL	0.2328		0.2371		0.2020	
R^2 MODEL	0.8301		0.8329		0.8519	
R^2 $g(\cdot)$	0.6980		0.6990		0.7872	



N=50 N=100 N=150

Figure 2: Scatter diagram of true link function and estimated link function using SMAVE estimation method.

To evaluate the model's performance more accurately and to ensure measuring its generalization ability rather than relying solely on the training data performance, the total sample was divided into two subsets: a training set and a testing set. Specifically, 70% of the individuals were allocated for training, while the remaining 30% were reserved for testing. The LSTM model was trained exclusively on the training set, whereas the testing set was used to evaluate the model and calculate the performance metrics.

The estimates for the linear parameters θ_1 and θ_2. The mean squared error (MSE) for the parameters θ is very low across all sizes, and in some cases reaches values very close to zero, indicating a good ability of the model to recover the linear parameters. The bias is also small (<0.02), which enhances the reliability of the estimate (Table 1).

Estimates of the indicator vector β at N=150 show a significant improvement in the estimate, with the MSE and bias being relatively smaller compared to smaller values, especially for the parameters β_2 and β_3. In contrast, at N=50, the bias is relatively larger for some components (e.g., β_2), an expected behavior with a small sample size.

The mean square error of the estimate of the nonlinear function $g(\cdot)$ is very low (<0.001), reflecting a high accuracy in representing the nonlinear relationship. The relationship between the true and estimated link functions obtained using the LSTM method is illustrated in Figure 1.

The determined coefficient R^2 for the estimate of $g(\cdot)$ is close to 1 (approximately 0.999), demonstrating excellent estimation quality in all cases. Goodness of fit of the overall model the mean squared error of the full model decreases with increasing sample size (from 0.123 at N=100 to 0.1009 at N=150). R^2 for the full model increases slightly with increasing sample size, reaching about 0.927 at N=150, indicating a high fit.

The three graphs show a comparison between the true values of the nonlinear function $g(u)$ (blue dots) and the estimated values (red circles) across different sample sizes N=50, 100, and 150 (Fig. 1). The following observations can be drawn: At all three sample sizes, the estimate appears to agree very closely with the true shape of the function, with clear convergence between the blue dots and red circles. As the sample size increases (from 50 to 150), the dispersion around the true curve decreases, and the estimated values become smoother and more stable. This reflects the improved accuracy with increasing sample size, which is theoretically expected in semiparametric estimation.

The results indicate that the estimation of the linear coefficients (θ_1, θ_2) has a high degree of accuracy, as the mean deviation (Bias) and mean squared error (MSE) values remained relatively low across all sample sizes (Table 2). In contrast, the single-index coefficients $(\beta_1, \beta_2, \beta_3)$ recorded high bias, especially for the smaller sample (N=50). The bias for β_1, β_2 reached 0.4257 and 0.2013, respectively, with MSEs of 0.1812 and 0.04054, reflecting poor estimation accuracy in the nonlinear part of the model. The estimation results of the function $g(\cdot)$ also showed inconsistent performance, with the highest MSE recorded at N=100, at 0.1347, despite a low bias (0.0042), which may indicate fluctuations in the estimate resulting from the nature of the function or the sample size. As for the quality of the model as a whole, the performance indicators showed that the model's coefficient of determination (R^2 MODEL) gradually decreased from 0.8519 at N=150 to 0.8301 at N=50. Meanwhile, the accuracy of the representation of the function $g(\cdot)$ was significantly lower, with its R^2 reaching 0.6980 at N=50, demonstrating the superiority of the deep neural network method used in estimating the link function.

For the three plots in all three sizes, the estimate appears to be inconsistent with the true form of the function, indicating the difficulty of smoothing methods in interpreting the relationship for a nonlinear function (Fig. 2).

5 CONCLUSIONS

Comparison results between LSTM and SMAVE estimation methods on a Partial Linear Single Index Model (PLSIM) for longitudinal data showed a clear superiority of LSTM in terms of the accuracy of estimating linear and nonlinear parameters and the stability of results across different sample sizes. LSTM recorded very low MSE and deviation values in estimating the parameters θ and β, and demonstrated excellent performance in estimating the nonlinear function $g(\cdot)$ with R^2 values exceeding 0.99, reflecting its ability to capture complex relationships in longitudinal data. In contrast, SMAVE showed less accurate results, particularly in estimating the parameters β and the function $g(\cdot)$, where the MSE and Bias values were relatively high, especially at small sample sizes, indicating that it is affected by the choice of bootstrap parameters and the difficulty of estimation with limited samples. LSTM also outperformed in overall model quality, achieving the highest R^2 for the model, demonstrating a better fit to the data and superior prediction, while SMAVE was less stable and performed less well. Thus, these results demonstrate that LSTM represents a more efficient and accurate option for analyzing and estimating PLSIM models with longitudinal data compared to traditional semiparametric methods.

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Reliability Estimation of the Alpha Power Fréchet Distribution Using MLE and GA

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Keywords: Alpha Power Fréchet. Power Alpha, Reliability, Maximum Likelihood, Genetic Algorithm.

Abstract: Studying failure data requires a flexible distribution to interpret the probabilistic behavior of these data. Therefore, the reliability function of the Alpha–Power Fréchet (APF) distribution was used to study the failure data. The Alpha power transformation was applied to the classical Fréchet distribution to develop a more flexible model capable of handling heterogeneous datasets. The probability density function, cumulative distribution function, and the corresponding reliability function for the APF distribution were derived. The maximum likelihood method and the genetic algorithm were used to estimate the reliability function of the Alpha–Power Fréchet distribution. A simulation study was conducted with various sample sizes (ranging from n=15 to n=500) and multiple different parameter combinations to evaluate the performance of both estimators. The comparison was based on the Mean Squared Error (MSE) criterion. The results revealed that the maximum likelihood method (MLE) showed a decrease in MSE values directly proportional to the increase in sample size, confirming its consistency and superior accuracy for large samples. Meanwhile, the genetic algorithm (GA) showed a robust performance that outperformed the maximum likelihood method for small and medium samples, making it a viable alternative in such cases, despite a noted tendency to slightly overestimate the reliability value.

1 INTRODUCTION

The Fréchet distribution is one of the most important distributions in the exponential family, and it can be used to describe the probabilistic behavior of data containing outliers or extreme values. This distribution is often used in the fields of hydrology, meteorology, finance, and engineering to characterize rare events. It is known as the inverse of the Weibull distribution, and is also known as the extreme value distribution of the second kind. It is used to model the maximum (or minimum) distribution of a large set of identically distributed independent random variables. The probability density function of the Fréchet distribution [1] is

$$\mathrm{f}(\mathrm{x},\beta,\lambda) = \frac{\lambda}{\beta}\left(\frac{x}{\beta}\right)^{-(\lambda+1)} e^{-\left(\frac{x}{\beta}\right)^{-\lambda}}, \; x > 0. \quad (1)$$

The distribution function is

$$F(x,\beta,\lambda) = e^{-\left(\frac{x}{\beta}\right)^{-\lambda}}. \quad (2)$$

The problem of the study was to search for probability distributions that can describe the random behavior of failure data of devices and equipment, which includes heterogeneous data, by finding flexible distributions that are found by searching for ways to expand traditional distributions. The problem of the study was also to search for accurate estimation methods to estimate the reliability function of expanded distributions in light of the development of computer programming languages such as the Python programming language. This study aims to compare two types of estimation methods: parametric estimation methods, represented by maximum likelihood, and artificial intelligence methods.

2 ALPHA FRÉCHET POWER DISTRIBUTION

The alpha Fréchet power distribution was proposed by finding an expansion of the Fréchet distribution and applying the formula below [2].

$$f_{APT}(x) = \frac{\log(\alpha)}{\alpha - 1} f(x)\alpha^{F(x)}, \alpha > 0, \alpha \neq 1. \quad (3)$$

If f(x) represents the density function of the distribution to be expanded, F(x) represents the cumulative function of the distribution, then by substituting (1) and (2) into (3), the probability density function of the Fréchet alpha power distribution is obtained, as shown in the equation:

$$f_{APT}(x) = \frac{\log(\alpha)}{\alpha - 1} \frac{\lambda}{\beta} \left(\frac{x}{\beta}\right)^{-(\lambda+1)} e^{-\left(\frac{x}{\beta}\right)^{-\lambda}} \alpha^{e^{-\left(\frac{x}{\beta}\right)^{-\lambda}}}, \quad (4)$$

$$\alpha > 0, \alpha \neq 1.$$

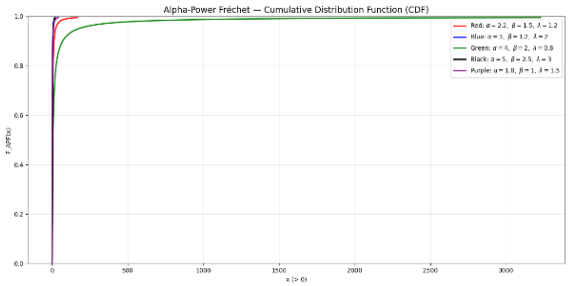


Figure 1: The figure represents the probability density function of the Alpha Power Fréchet distribution.

To obtain the cumulative function of the proposed distribution, we can apply the expansion equation for the cumulative function with the power of alpha (5):

$$F_{APT}(x) = \frac{\alpha^{F(x)} - 1}{\alpha - 1}, \alpha > 0, \alpha \neq 1. \quad (5)$$

After applying the expansion and using the cumulative function of the original distribution, the cumulative function of the proposed distribution is obtained.

$$F_{APT}(x) = \frac{\alpha^{e^{-\left(\frac{x}{\beta}\right)^{-\lambda}}} - 1}{\alpha - 1}, \alpha > 0, \alpha \neq 1. \quad (6)$$

The reliability function for the alpha power distribution is [3].

$$R_{APT}(x) = 1 - F_{APT}(x).$$

$$R_{APT}(x) = 1 - \frac{\alpha^{e^{-\left(\frac{x}{\beta}\right)^{-\lambda}}} - 1}{\alpha - 1}. \quad (7)$$

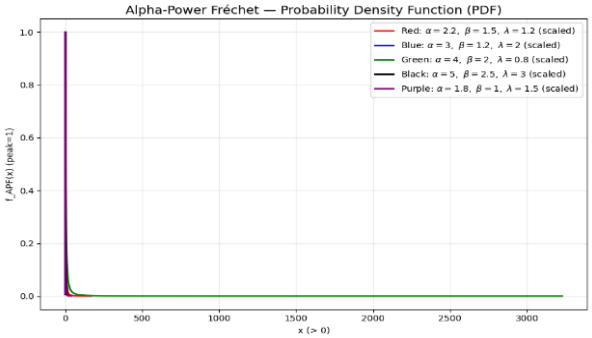


Figure 2: The figure represents the cumulative function of the Alpha Power Fréchet distribution.

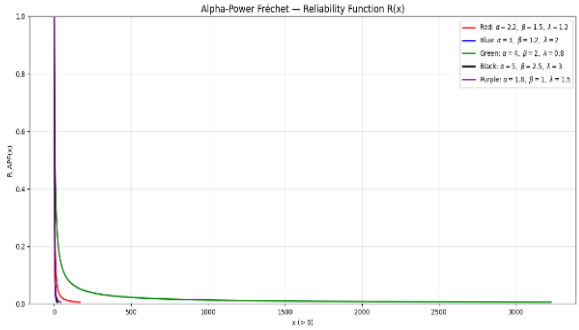


Figure 3: The figure represents the Reliabilityfunction of the Alpha Power Fréchet distribution.

3 ESTIMATING THE FRÉCHET ALPHA POWER DISTRIBUTION

The parameters and the reliability function of the Fréchet alpha power distribution were estimated using two methods: the maximum likelihood method and the genetic algorithm method, where the function was taken.

3.1 Estimation by the Maximum Likelihood Method

This method is one of the most common and widely used estimation methods among researchers, as it produces estimators that possess the characteristics of a good estimator, such as unbiasedness, stability [4], and consistency. This method estimates the parameters by maximizing the logarithm of the maximum likelihood function.

The equation below represents the logarithm of the maximum likelihood function for the Fréchet alpha power distribution [5], [6].

$$L(\theta) = \prod_{i=1}^{n} f(x_i;\theta), \quad (8)$$

$$L(\theta) = \prod_{i=1}^{n}\left(\frac{ln(\alpha)}{\alpha-1}\frac{\lambda}{\beta}\left(\frac{x_i}{\beta}\right)^{-(\lambda+1)} e^{-\left(\frac{x_i}{\beta}\right)^{-\lambda}} \alpha^{e^{-\left(\frac{x_i}{\beta}\right)^{-\lambda}}}\right), \quad (9)$$

$$L(\theta) = \left(\frac{l\,n(\alpha)}{\alpha-1}\right)^{n}\left(\frac{\lambda}{\beta}\right)^{n} \cdot \left(\sum_{i=1}^{n}\left(\frac{x_i}{\beta}\right)^{-(\lambda+1)} e^{\sum_{i=1}^{n}\left(\frac{x_i}{\beta}\right)^{-\lambda}} \alpha^{e^{\sum_{i=1}^{n}\left(\frac{x_i}{\beta}\right)^{-\lambda}}}\right). \quad (10)$$

Taking the natural logarithm of the function factorial

$$\begin{aligned} log(L(\theta)) = \\ = n\,ln(ln(\alpha)) - n * ln(\alpha-1) + n\,ln(\lambda) - n \\ * ln(\beta) - (\lambda+1)\,ln\left(\sum_{i=1}^{n}\frac{x_i}{\beta}\right) \\ + \sum_{i=1}^{n}\left(\frac{x_i}{\beta}\right)^{-\lambda} \\ + ln(\alpha)\,e^{-\left(\sum_{i=1}^{n}\left(\frac{x_i}{\beta}\right)^{-\lambda}\right)}. \end{aligned} \quad (11)$$

To obtain the estimators of the parameters of the probability density function for the alpha-force distribution (α, β, λ), the partial derivative of the logarithm of the probability function is taken as follows [7]:

$$\frac{\partial \mathcal{L}}{\partial \alpha} = \frac{\mathrm{n} - \mathrm{n}\alpha - \sum \mathrm{e}^{-\left(\frac{\mathrm{x_i}}{\beta}\right)^{-\lambda}}}{\alpha}, \quad (12)$$

$$\frac{\partial \mathcal{L}}{\partial \beta} = \frac{\lambda}{\beta}\left(\frac{x_i}{\beta}\right)^{-\lambda} + \frac{\lambda \mathrm{l\,n}(\alpha)}{\beta}\sum\left(\left(\frac{x_i}{\beta}\right)^{(-\lambda)} e^{-\left(\frac{x_i}{\beta}\right)^{-\lambda}}\right) - \frac{n(\beta-\lambda-1)}{\beta}, \quad (13)$$

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial \lambda} = \\ = n - \left(\frac{x_i}{\beta}\right)^{-\lambda} \mathrm{l\,n}\left(\frac{x_i}{\beta}\right) - \sum\left(\mathrm{l\,n}\left(\frac{x_i}{\beta}\right)\right) \\ - \mathrm{l\,n}(\alpha)\sum\left(\left(\frac{x_i}{\beta}\right)^{-\lambda} \mathrm{l\,n}\left(\frac{x_i}{\beta}\right) \mathrm{e}^{\left(-\left(\frac{x_i}{\beta}\right)^{-\lambda}\right)}\right). \end{aligned} \quad (14)$$

3.2 Estimation Using the Genetic Algorithm

The genetic algorithm is described as a heuristic method that simulates the idea of adapting to complex data and equations [8]. Its philosophy is based on the fact that, instead of relying on a single solution, a community of hypotheses is built, and these mechanisms compete through selection [9], mating, and mutation. With this approach, randomness is systematically used not only to break the stability of the results, but also to open new paths in the solution space and avoid falling into weak local optimization. The success of the GA also depends on the quality of the coding and the suitability of the fitness function to the statistical objective [10]. The problem is formulated by estimating the parameters of the APF distribution, i.e.,θ = (α, β, λ), through a positive simulation sample x_1, x_n. With the parameters α > 1, β > 0, and λ > 0, we measure the quality of the parameters (α, β, λ) using a criterion, which is the logarithm of the likelihood function for the data under the APF model, where the fitness function (Fitness = –log-likelihood), with the goal of minimizing the cost. Initial values for the parameters (α, β, λ) are generated using a hybrid method that considers diversity and objectivity in the form of seeds. We place at least two widely spaced seeds, such as (α=2, β=2, λ=2) and (α=12, β=4, λ=3) [10], to cover different gates in the solution space. An initial population is then generated around these individuals, adding small differences for each parameter while clipping within the bounds. The goal is to start the search from known but diverse points, ensuring exploratory power in the first generations. All the parameters that have been taken go through the testing stage using the fitness function taken from the logarithm of the factorial of the probability function of the proposed distribution, as in (11) above.

$$\begin{aligned} log(L(\theta)) = n * ln(ln(\alpha)) - n * ln(\alpha-1) + n * \\ ln(\lambda) - n * ln(\beta) - (\lambda+1) * ln\left(\sum_{i=1}^{n}\frac{x_i}{\beta}\right) + \\ \sum_{i=1}^{n}\left(\frac{x_i}{\beta}\right)^{-\lambda} + ln(\alpha) * e^{-\left(\sum_{i=1}^{n}\left(\frac{x_i}{\beta}\right)^{-\lambda}\right)}. \end{aligned}$$

The above equation is used to find the fitness function.

$$Fitness(\alpha,\beta,\lambda) = -\sum_{i=1}^{n} log\ f_{APF}(x_i;\alpha,\beta,\lambda). \quad (15)$$

Next, we move to the selection step, where we use tournament selection (k = 3) to select the best parents by taking three random hypotheses and choosing the values with the highest fit. We repeat the process twice to select two parents. We apply simple elitism by transferring the best one or two types of individuals as they are to the next generation. Next comes the crossover, which takes two forms. The first is a single cut on the vector [α, β, λ] by swapping the positions of the parameters after the cut that fall on

the parents, for example, the right of the first with the left of the second and the left of the first with the right of the second. The second type of crossover is linear crossover, which is done by constructing the two offspring as a linear mixture of the parents with a mixing coefficient r ~ U (0,1) according to the following two equations [11], [12]:

$$C_1 = r\,p_1 + (1 - r)p_2. \quad (16)$$
$$C_2 = r\,p_2 + (1 - r)p_1. \quad (17)$$

Where:

- C1, C2: children,
- P1, P2: parents
- r: mixing coefficient.

This type maintains continuity in the parameter space and allows for smooth jumps between solutions. Next, we move to the most important section, which adds the concept of randomness to the genetic algorithm: mutation. A random value is added to each gene by a small amount, for example, 0.001, to move from broad exploration to fine-tuning. After mating and mutation, we move to the repair and constrain section, where we return α, β, and λ to the allowed range. We then examine which numerical states ultimately lead to the stopping criterion, which could be a maximum number of generations (such as 100 generations), or a random error difference between the actual and estimated values, which is small enough to allow for the best-known solution at the stopping moment. The estimation is evaluated according to the criteria used in this research, the mean error standard (MSE) for reliability, using Monte Carlo iterations [9], [10], [11].

4 SIMULATION

The simulation in this research presents the experimental methodology adopted to compare the accuracy and reliability of the Alpha Power Fréchet distribution parameter estimation methods at (n= 15, 25, 35, 50, 75, 100, 500) observations, each segment representing a fixed time period used to calculate the number of operating units at the beginning of the period and the number of errors or failures (faults) recorded during it. Based on this information, the reliability function was estimated. All the above operations and default parameter values were included in Table 1 to calculate the potential and genetic algorithm [12]. The objective of this section is to evaluate the performance of each method using the mean square error (MSE) criterion via Monte Carlo simulation.

Table 1: Default values for the parameters (α, β, λ) for the (Alpha Power Fréchet) distribution.

α	2	4	12	25	3
β	2	1	4	10	0.2
λ	2	6	3	1	5

The Invers method was used to obtain the tracking variables of the Alpha Power Fréchet distribution according to the following formula.

$$X = \beta * \left(-ln\left(\frac{ln(R*\alpha - R+1)}{ln(\alpha)}\right)\right)^{-\frac{1}{\lambda}}. \quad (18)$$

Where α is the location parameter, β is the scaling parameter, and λ is the shape parameter. The simulation was repeated 2000 times.

Table 2: Results of simulation of the maximum likelihood method for the reliability of the Alpha Power Fréchet distribution for default parameter.

	values at (α=2; β=2; λ=2)			
	(α=2;β=2;λ=2)			
	MLA		*GA*	
n	Reliability	MSE	Reliability	MSE
15	0.53116	0.00320	0.2633	0.0795
25	0.52787	0.00268	0.2601	0.0742
35	0.52269	0.00202	0.2589	0.0721
50	0.52095	0.00156	0.2593	0.0708
75	0.51819	0.00092	0.2609	0.0708
100	0.51482	0.00077	0.2594	0.0693
500	0.50656	0.00014	0.2611	0.0689

As shown in Table 2, which displays the reliability values and their Mean Squared Error (MSE) for both the maximum likelihood method and the genetic algorithm under the parameter set (α=2, β=2, λ=2), it is observed that the MSE for the maximum likelihood estimator is lower than that of the genetic algorithm for all sample sizes.

Table 3: Results of simulation of the maximum likelihood method for the reliability of the Alpha Power Fréchet distribution for default parameter.

	values at (α=4; β=1; λ=6)			
	(α = 4; β = 1; λ = 6)			
	MLA		*GA*	
n	Reliability	MSE	Reliability	MSE
15	0.54027	0.00434	0.58601	0.34355
25	0.53034	0.00308	0.59008	0.34823
35	0.52443	0.00239	0.59142	0.34979
50	0.51956	0.00136	0.59210	0.35059
75	0.51705	0.00077	0.59248	0.35104
100	0.51377	0.00063	0.59261	0.35118
500	0.50540	0.00009	0.59278	0.35139

As shown in Table 3, which displays the reliability values and their Mean Squared Error (MSE) for both the maximum likelihood method and the genetic algorithm under the parameter set (α=4, β=1, λ=6), it is noted that the MSE for the maximum likelihood estimator is substantially lower than that of the genetic algorithm across all sample sizes.

Table 4: Results of simulation of the maximum likelihood method for the reliability of the Alpha Power Fréchet distribution for default parameter.

	values at (α=12; β=4; λ=3)			
	$(\alpha = 12; \beta = 4; \lambda = 3)$			
	MLA		GA	
n	Reliability	MSE	Reliability	MSE
15	0.50928	0.00611	0.2566	0.0763
25	0.51102	0.00372	0.2586	0.0736
35	0.51291	0.00269	0.2621	0.0737
50	0.51379	0.00201	0.2592	0.0712
75	0.51467	0.00138	0.2607	0.0706
100	0.50928	0.00611	0.2566	0.0763
500	0.51102	0.00372	0.2586	0.0736

As illustrated in Table 4, which compares the reliability estimates and their Mean Squared Error (MSE) for the maximum likelihood and genetic algorithm methods using the parameters (α=12, β=4, λ=3), it is evident that the MSE of the maximum likelihood estimator is consistently lower than that of the genetic algorithm across all sample sizes.

Table 5: Results of simulation of the maximum likelihood method for the reliability of the Alpha Power Fréchet distribution for default parameter.

	values at (α=25; β=10; λ=1)			
	$(\alpha = 25; \beta = 10; \lambda = 1)$			
	MLA		GA	
n	Reliability	MSE	Reliability	MSE
15	0.46535	0.00385	0.82066	0.67429
25	0.47263	0.00223	0.83063	0.69012
35	0.47636	0.00143	0.83370	0.69512
50	0.47978	0.00118	0.83542	0.69794
75	0.48469	0.00090	0.83675	0.70015
100	0.48600	0.00061	0.83709	0.70071
500	0.49409	0.00011	0.83762	0.70161

The results presented in Table 5, which details the reliability estimates and their corresponding Mean Squared Error (MSE) for the maximum likelihood and genetic algorithm methods under the parameter configuration (α=25, β=10, λ=1), demonstrate that the MSE for the maximum likelihood estimator is consistently lower than that of the genetic algorithm for every sample size examined.

Table 6: Results of simulation of the maximum likelihood method for the reliability of the Alpha Power Fréchet distribution for default parameter.

	values at (α=3; β=0.2; λ=5)			
	$(\alpha = 3; \beta = 0.2; \lambda = 5)$			
	MLA		GA	
n	Reliability	MSE	Reliability	MSE
15	0.53845	0.00467	0.63422	0.40342
25	0.53362	0.00404	0.64661	0.41846
35	0.52127	0.00179	0.65139	0.42444
50	0.52134	0.00159	0.65472	0.42869
75	0.51747	0.00082	0.65634	0.43079
100	0.51372	0.00064	0.65690	0.43152
500	0.50633	0.00013	0.65770	0.43257

Table 6 presents the reliability estimates and their corresponding Mean Squared Error (MSE) for the maximum likelihood and genetic algorithm methods, given the parameters (α=3, β=0.2, λ=5). The results indicate that the MSE for the maximum likelihood estimator is lower than that of the genetic algorithm across all examined sample sizes.

5 CONCLUSIONS

Based on the comprehensive simulation study, the following key conclusions can be drawn:

1) The Maximum Likelihood (MLE) method demonstrates superior performance over the Genetic Algorithm (GA) in estimating the reliability function of the Alpha Power Fréchet distribution. This conclusion is consistently supported by lower Mean Squared Error (MSE) values across all tested sample sizes and parameter sets (α,β,λ)(α,β,λ).
2) The MLE method shows the property of consistency: its estimation error (MSE) decreases systematically as the sample size increases (from n=15 to n=500). This indicates that the estimates converge to the true parameter values with more data.
3) The reliability values estimated by GA are consistently higher than those obtained via MLE for the same parameters, indicating a slight upward bias in the GA estimates. Nevertheless, GA shows robust performance, particularly at small to medium sample sizes, making it a viable alternative when classical methods like MLE are difficult to implement due to computational or analytical complexities.

For estimating the reliability of the Alpha Power Fréchet distribution, the Maximum Likelihood

method is recommended due to its higher accuracy and consistency. The genetic algorithm serves as a competent complementary tool, especially in challenging scenarios where traditional optimization fails.

RECOMMENDATIONS

Based on the results, the maximum likelihood (MLE) method is recommended as the primary approach for estimating the reliability function of the Alpha Power Fréchet distribution, particularly for large sample sizes ($n \geq 50$), due to its high accuracy and consistency. The genetic algorithm (GA) is suggested as an alternative estimation method, offering robustness and effectiveness, especially for small or medium sample sizes or when the likelihood function is complex. A hybrid approach can also be developed, combining the advantages of both methods, where the GA is used to determine optimal parameter values that are then employed as initial values for the MLE algorithm to achieve high optimization accuracy. It is further recommended to apply both methods to real data from engineering and machinery fields to validate these results and compare performance in practical applications. Additionally, the study could be expanded to include other performance evaluation metrics, such as bias (BIAS), and the performance of the genetic algorithm can be enhanced by fine-tuning parameters like mutation rate, population size, and breeding method to achieve higher accuracy and lower mean square error (MSE).

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Joint Longitudinal-Survival Modelling of Childhood Leukemia Using EM Algorithm

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Keywords: Joint Model, Longitudinal and Survival Data, Model Evaluation (AIC, RMSE), EM Algorithm.

Abstract: This Study aims to assess the impact of certain clinical factors on children with leukemia by employing The Joint Model for Longitudinal and survival data, using the Expectation–Maximization (EM) algorithm for parameter estimation. In this research, the longitudinal data are represented by repeated measurements of hemoglobin (Hb) levels over time, while the survival data correspond to the follow-up time until the realization of the event (death or censoring). The results revealed that Hb levels significantly decrease over time ($p < 0.0001$). Female patients had lower Hb levels compared to males ($p=0.006$), while older age was associated with slightly higher Hb values ($p=0.0002$). In the survival sub-model, the effects of age and sex were statistically insignificant ($p > 0.05$). Importantly, the negative and significant association parameter (γ, $p=0.0001$) indicated that higher Hb levels reduce the risk of death, highlighting the predictive value of longitudinal information in explaining survival outcomes. Based on the goodness-of-fit criteria (AIC and RMSE), the EM algorithm demonstrated high efficiency in estimating the parameters of the joint model and achieving strong agreement between predicted and observed values. Therefore, the joint model provides a powerful and effective tool for integrating longitudinal and survival information in the study of childhood leukemia, enhancing estimation accuracy and enabling more reliable conclusions about the factors influencing disease progression.

1 INTRODUCTION

Childhood leukemia is one of the most common and serious types of cancer, posing a major challenge to healthcare systems due to its direct impact on survival rates and patients' quality of life. Studying the factors that influence disease progression and survival among affected children is a crucial step toward improving diagnostic and therapeutic strategies. In this context, advanced statistical models have become essential to capture the complexity of medical data, which often consist of repeated longitudinal measurements of biological markers alongside survival outcomes [1], [2].

The Joint Model for Longitudinal and survival data is considered one of the most powerful tools in this field. It integrates longitudinal information (such as hemoglobin levels) with survival outcomes (time-to-event) within a unified framework, providing more accurate estimates and enabling the study of dynamic relationships between biomarkers and the risk of mortality [3]. Several estimation methods have been developed for this model, with the Expectation–Maximization (EM) algorithm being among the most widely used due to its efficiency in handling missing data and complex parameters [4], [5].

This study aims to apply The Joint Model using the EM algorithm to measure the effect of demographic and clinical factors (such as age and sex) on children with leukemia, with a particular focus on the relationship between changes in hemoglobin over time and survival probability. The research also provides interpretation of the estimation results and highlights conclusions that may contribute to supporting medical decision-making and improving healthcare for this vulnerable group of patients.

2 JOINT MODELS

The concept of Joint Models is based on the modeling of two types of data that form two components within the model. This modeling helps to understand how these data depend on each other, leading to better results, more accuracy, less bias, and more accurate

predictions [1], [4]. Both data in a common model are modeled according to two components: the first records changes over time and the second monitors when events (deaths) occur. Wulfsohn and Tsiatis (1997) were the first to describe the joint model, as these models consist of two sub-models [1], [2].

2.1 Longitudinal Sub-Model

The first sub-model is a Mixed Effect sub-model for modeling longitudinal data, which represents repeated measurements of variables, such as measuring vital signs or monitoring the patient's response to treatment over time. It tracks changes and differences between measurements, such as disease progression or treatment effectiveness. Longitudinal data are often modeled using the Linear Mixed-Effect model, which studies fixed effects representing overall trends and random effects representing individual differences, thereby capturing both population-level trends and individual variations [4], [6]. In addition, the analysis of high-dimensional longitudinal data has become increasingly important, where joint modeling provides a robust framework for addressing complexity and ensuring reliable inference [7].

2.2 Survival Sub-Model

The second sub-model represents the modeling of the time of occurrence of events (e.g., death) based on survival data analysis. The time until the occurrence of the event is observed, with examples including the proportional hazards model and accelerated failure time models. These models estimate the risk or timing of an event. The Cox proportional hazard semi-parametric model is the most common approach, as it evaluates how different factors affect the risk of an event without assuming restrictions on event times [2], [8].

2.3 Combined Joint Model

Joint models integrate both sub-models by allowing the survival component (event occurrence time) to depend on some characteristics of the longitudinal sub-model through various methods [1], [5]. A key feature of joint models is that longitudinal data from a given time until the event is modeled simultaneously with a conditional joint density function, rather than treating the two sub-models as independent [4], [9].

To formulate the joint model, some terms must be defined:

- T_i^*: denotes the true occurrence time of the event for subject *i*;
- T_i: represents the observed time for subject *i*;
- δ_i : is the event index equal to (1) when the real event occurs;
- y_i: is the longitudinal response variable;
- The formulation of the joint model generally involves three stages [1], [10].

2.1 Constructing the Survival Data Sub Model

Let T_i^* be the true event time for subject $(i = 1, 2, \dots, n)$, and let T_i denote the observed survival time. If the subject does not experience the event during the study period, T The observation for subject i is right-censore. Let C_i be the potential censoring time such that:

$$T_i = min(T_i^*, C_i).$$

Define the event indicator as:

$$\delta_i = \begin{cases} 1 \text{ if the true event is observed;} \\ 0 \text{ if the event is right} - \text{censored.} \end{cases}$$

Thus, the observed survival data can be written as: [5], [10]

$$\{(T_i, \delta_i);\ i = 1,2, \dots, n\}.$$

For the i^{th} subject, let $y_i(t)$ denote the observed longitudinal measurement at time point t_{ij}, for *j=1, 2, …,* m_i. Let m_i (t) denote the true longitudinal trajectory of subject i, which is unobserved and differs from $y_i(t)$.

To describe the association between the longitudinal trajectory and the hazard of an event, the proportional hazards model is given by:

$$h_i(t \mid \mu_i(t)) = \lim_{\delta t \to 0} \left\{ \frac{p[t \leqslant T_i^* < t + \delta t \setminus T_i^* \geqslant t, \mu_i(t), w_i]}{\delta t} \right\} = h_0(t)\, exp\{\gamma^\top w_i + \alpha m_i(t)\}, \ t > 0, \quad (1)$$

where:

- $m_i(t)$represents the true values of the time-dependent longitudinal covariates at time *t.*;
- $h_0(t)$ is the unspecified baseline hazard for a subject with all explanatory covariates equal to zero;
- w_i is the vector of baseline explanatory covariates;
- γ is the vector of regression coefficients corresponding to w_i;

- α is the association parameter measuring the effect of the longitudinal data on survival outcomes at time.[4], [10].

The hazard function in (1) assumes that the risk of experiencing the event at time *t*. depends only on the current value of $m_i(t)$, which changes over time.

Based on the relationship between the survival function and the cumulative hazard function, the survival probability can be expressed as:

$$S_i\big(t \setminus M_i(t)\big) = Pr(\tau_i^* > t \setminus \mu_i(t), w_i) = exp\left(-\int_0^t h_0(s)\exp\{\gamma^\top w_i + \alpha M_i(s)\}ds\right). \quad (2)$$

This expression represents the survival function for subject i, conditional on the entire longitudinal process $m_i(t)$ [4], [6]

2.2 Constructing the Longitudinal Sub-Model

The hazard function $h_i\ (t)$ in (1) depends on the true longitudinal outcomes $m_i(t)$ at time t. For each subject, the true longitudinal process is recorded at intermittent time points $\{t_{ij}, j=1, 2,\ldots,m_i\}$, subject to measurement errors. To relate the longitudinal outcomes to the risk of event occurrence, it is necessary to estimate $m_i(t)$.

Therefore, the longitudinal data are modeled using the Linear Mixed-Effects Model (LME). For the i^{th} subject, the observed longitudinal responses are given by:

$$y_{ij}\ (t_{ij}), j=1, 2,\ldots,m_i.$$

Assuming that the longitudinal outcomes follow a normal distribution, the linear mixed-effects model can be specified as follows:

$$y_i(t) = x_i^\tau(t)\beta + z_i^\tau(t)b_i + \epsilon_i(t), \quad (3)$$

$$y_i(t) = m_i(t) + \epsilon_i(t), \quad (4)$$

$$m_i(t) = x_i^\tau(t)\beta + \epsilon_i^\tau(t)b_i. \quad (5)$$

Here, b_i follows a multivariate normal distribution with covariance matrix D, i.e.,

$$b_i \sim N(0, D).$$

The random error term is assumed as $\epsilon_i(t) \sim N(0, \sigma^2)$, and is mutually independent of b_i.

Where:

- $x_i(t)$, β*:* represent the fixed effects;
- $z_i(t), b_i$: represent the random effects;
- $\epsilon_i(t)$: denotes the random error term for subject i at time *t.* [4], [6]

2.3 Constructing the Joint Model

The Joint Model for Longitudinal and survival data consists of two sub-models that are linked together, and all parameters are estimated simultaneously. The Mixed-Effects Model is one of the most commonly used approaches for modeling longitudinal data, while the Proportional Hazards Model is typically employed to handle survival data with time-dependent covariates.

The association between the two sub-models may occur through random effects or regression parameters. To construct The Joint Model for Longitudinal and Survival Data, the following steps are generally taken [5], [11].

1) Specify the trajectory function for the longitudinal process, which correctly represents its evolution over time.
2) Define the structure of the longitudinal component based on the observed values.
3) Specify the appropriate model for the survival component.

The trajectory function plays a central role by representing the true values of the longitudinal covariate across all time points, including unobserved times (free of measurement error). Thus, it allows us to capture both the underlying trajectory of the covariate and its time-dependent effect [9], [12].

The trajectory function can be defined as:

$$W_i(t) = z(t)\ b_i\ \ , t > 0, i = 1,2, \ldots, n \ldots, (6)$$

where:

- $W_i(t)$denotes the trajectory function of subject i at time t, representing the true value of the longitudinal covariate regardless of whether an observation is available at that time;
- $z(t)$ is a vector of continuous functions;
- b_i is the vector of subject-specific random effects (including random intercepts and slopes).

After defining the trajectory, it can be related to the observed longitudinal measurements: [6], [10].

$$y_i = (y_i\ (t_{i1}), y_i\ (t_{i2}), \ldots, y_i\ (t_{iJ_i})$$

with:

$$y_i(t_{ij}) = w_i(t_{ij}) + \epsilon_i(t_{ij})\ \ ;\ i\ = 1, 2, \ldots n. \quad (7)$$
$$j = 1, 2, \ldots J_i = x_i\beta + z_i(t_{ij})^\top b_i + \epsilon_i(t_{ij})$$

where:

- -$y_i(t_{ij})$: observed longitudinal outcome for subject i at time t_{ij};

- $w_i(t_{ij})$: trajectory function, consisting of both fixed and random effects;
- x_i: vector of baseline covariates for subject i;
- β: vector of fixed-effects coefficients;
- z_i: time-dependent design vector;
- b_i: vector of random effects, assumed $b_i \sim N(\mu_b, \Sigma_b)$;
- $\epsilon_i(t_{ij})$: error term, assumed $\epsilon_i(t_{ij}) \sim N(0, \sigma_\epsilon^2)$.

The proportional hazards model can then be extended to incorporate the time-dependent trajectory function:

$$h(u_i) = \lim_{d_u \to 0} \frac{p(u_i \leqslant T_i < u_i + d_u \mid T_i \geqslant u_i, w_i^H(u_i) z_i b_i}{d_u}. \quad (8)$$

$$h(u_i) = h_0(u_i)\, exp\{\eta w_i(u_i) + z_i\theta\} \quad ; \; i = 1,2, \ldots, n.$$

The survival function is then expressed as:

$$\begin{aligned} S(u_i) &= exp\{-H(u_i)\} \\ &= exp\left\{-\int_0^{u_i} h(s)ds\right\} \\ &= ex\,p\{-\textstyle\int_0^{u_i} h_0(s)\exp\{\eta(w_i(s) + z_i\mu\}ds. \end{aligned} \quad (9)$$

Thus, combining the longitudinal and survival components, the joint likelihood function can be written as:

$$\begin{aligned} L(\theta; u_i, \delta_i, y_i, t_i, x_i, z_i) &= \prod_{i=1}^{n} p(u_i, y_i \mid \theta) \\ &= \textstyle\prod_{i=1}^{n} \int [h_0(u_i) ex\, p(\eta\omega_i(u_i) + \\ & z_i\psi)]^{\delta_i} . ex\, p\{-\textstyle\int_0^{u_i} h_0(s) ex\, p(\eta\omega_i(s) + \\ & z_i\psi ds\}. \frac{1}{(2\pi\sigma_\epsilon^2)^{J_i/2}} ex\, p\left\{-\textstyle\sum_{j=1}^{J_i} \frac{\{Y_i(t_{ij}) - W_i(t_{ij})\}^2}{2\sigma_\epsilon^2}\right\}. \\ & p(b_i \mid \mu_b, \Sigma b) db_i. \end{aligned} \quad (10)$$

Under the assumption of full conditional independence, the joint distribution can be factored as:

$$P(y_i, T_i, \delta_i \mid b_i) = p(y_i \mid b_i) \cdot p(T_i, \delta_i \mid b_i). \quad (11)$$

$$P(y_i \mid b_i) = \prod_{j=1}^{m_i} p(y_{ij} \mid b_i). \quad (12)$$

Finally, the survival function conditional on random effects is:

$$S_i(t \mid b_i) = exp\left(-\int_0^t h_0(s) exp\{\gamma^\top w_i + \propto m_i(s)\} ds\right). \quad (13)$$

Hence, the joint likelihood can also be written as:

$$\begin{aligned} P(y_i, T_i, \delta_i) = \int\ & p(y_i \\ & \mid b_i)\{h(T_i \mid b_i)^{\delta_i} S(T_i \\ & \mid b_i)\} p(b_i) db_i. \end{aligned} \quad (14)$$

3 ESTIMATION METHOD FOR JOINT MODEl

After studying the concept of the joint model and identifying all of its components, the estimation methods for the joint model of the combined data will be examined based on equations (13), (14), and (15). In particular, the Maximum Likelihood Estimation (MLE) method will be studied [13].

3.1 Maximum Likelihood Method (MLE)

Wulfsohn and Tsiatis (1997), as well as Rizopoulos (2012), provided a detailed methodology for estimating the joint model using the Maximum Likelihood Estimation (MLE) approach [5].

$$\begin{aligned} & \log L_i(\theta) \\ &= log \int \left\{ \prod_{j=1}^{mi} p(y_{ij} \mid b_{ij}\theta)\{h(T_i \mid b_i; \theta)^{s_i} S_i(T_i \mid b_i; \theta)\} \right. \\ & \qquad \left. p(b_i; \theta) d\, b_i. \right. \end{aligned} \quad (15)$$

Since both integrals do not admit closed-form solutions, numerical approximation methods are required to estimate the joint model. Among these methods, the EM algorithm is widely used [5].

3.1.1 The Expectation–Maximization Algorithm (EM)

The EM algorithm, first developed by Arthur Dempster and colleagues in 1977, is a numerical technique primarily used for parameter estimation in models with incomplete data or latent variables. This algorithm addresses the implications associated with such models that cannot be estimated using traditional statistical methods, making it a pivotal tool for addressing specific challenges in data analysis. Therefore, the EM algorithm is of great importance in the fields of statistics and machine learning.

The purpose of using the EM algorithm is to maximize the likelihood function for models with unobserved data in order to improve prediction [4], [5].

By substantially enhancing statistical parameter estimates, the EM algorithm provides more accurate and reliable results, making it a valuable tool in various research and applied domains.

The basic steps for applying the EM algorithm to the joint model are as follows:

1) Basic equation:
   Represent the Maximum likelihood function for The Joint Model, which the EM algorithm seeks to maximize.

$$\log L_i(\theta) = log \int \left\{ \prod_{j=1}^{mi} p(y_{ij} \mid b_{ij}\theta)\{h(T_i \mid b_i;\theta)^{s_i} S_i(T_i \mid b_i;\theta)\} \right\} p(b_i;\theta) d\, b_i. \quad (16)$$

   Where:
   - y_{ij}: observed longitudinal data;
   - T_i: survival time for each patient;
   - b_i: random effects or latent (unobserved) variables;
   - θ: parameters to be estimated;
   - $h(T_i \mid b_i;\theta)$: conditional hazard function;
   - $S_i(T_i \mid b_i;\theta)$: conditional survival function.

2) E-step (Expectation step):

   Estimate the expected values of the random effects (b_i). Since these random effects are not directly observed, we compute their expectations based on the current parameter estimates:

$$Q(\theta \mid \theta^{(t)}) = E[log\ L_i(\theta) \mid y_{ij}, \tau_i, \theta^{(t)}].$$

   This expectation is obtained from the conditional distribution of the random effects.

3) M-step (Maximization step):
   Update the parameter estimates θ by maximizing the expectation

$$arg\ max_\theta Q(\theta \mid \theta^{(t)}). = \theta^{(t+1)}.$$

4) Iteration until convergence:

   Repeat the E-step and M-step until convergence, i.e., when the difference between successive estimates becomes sufficiently small [4], [5].

$$\theta^{(t+1)} - \theta^{(t)} \approx 0.$$

4 PERFORMANCE MEASURES

To evaluate the predictive performance of the proposed model, several statistical measures are employed. These measures provide a comprehensive assessment of the model's accuracy and efficiency. The most widely used criteria include:

1) The Root Mean Squared Error (RMSE). It is calculated according to the following [8], [10]:

$$RMSE = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(y_t - \hat{y_t})^2}, \quad (17)$$

2) Akaike Information Criterion (AIC). Used to evaluate model quality by balancing goodness of fit and model complexity [4], [10].
   AIC penalizes overfitting by incorporating the number of estimated parameters. It is defined as:

$$AIC = -2\ln(L) + 2k... \quad (18).$$

5 THE PRACTICAL APPLICATION

In this part, The Joint Model for Longitudinal and survival Data was applied using the R software to estimate the parameters and analyze the relationship between longitudinal variables and event time. Estimation methods were employed, and the results were evaluated using performance criteria such as RMSE and AIC to assess the efficiency of the model.

The Figure 1 presents Kaplan–Meier survival curves by sex, showing that the trajectories of males and females are very similar, with no statistically significant difference between the two groups (p=0.8), indicating that sex had no clear effect on survival probability during the follow-up period.

The Figure 2 illustrates the relationship between hemoglobin (Hb) levels and the hazard ratio (HR), showing that higher Hb levels are associated with lower hazard, indicating that increased Hb reduces the likelihood of the event and serves as an important indicator of improved survival.

Table 1 presents the estimation results of the joint longitudinal–survival model using the Expectation–Maximization (EM) algorithm. As shown in Table 1, the longitudinal sub-model indicates that the intercept is positive and highly significant, while time has a negative and statistically significant effect (p = 0.0001), reflecting a gradual decline in hemoglobin (Hb) levels over time. Age shows a positive and significant association with Hb levels (p = 0.0002), whereas female patients exhibit significantly lower Hb values compared to males (p = 0.006).

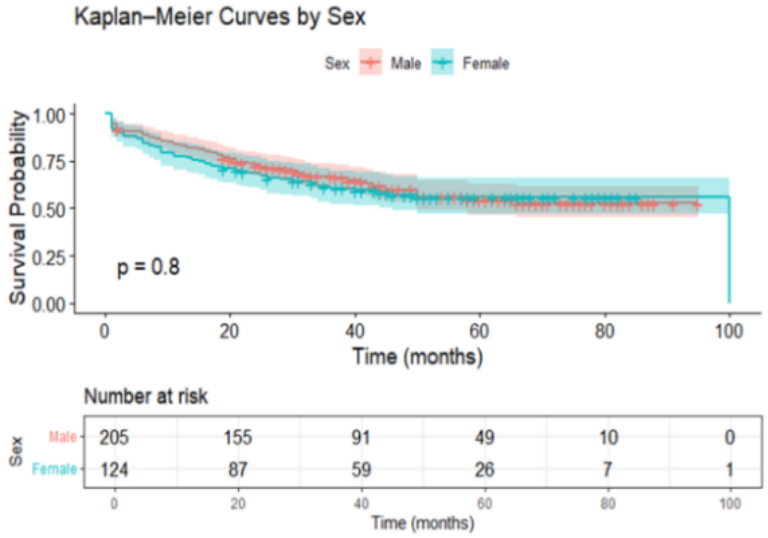


Figure 1: Kaplan–Meier survival curves were analyzed by sex.

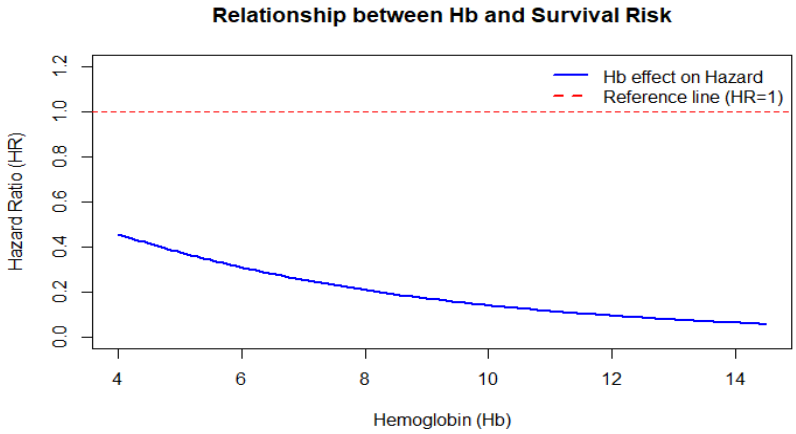


Figure 2: The parameter estimates of the joint model were obtained using the EM algorithm.

Table 1: Estimation Results of the Joint Model (EM).

Model Component	Variable /Parameter	Estimate	Std. Error	Z-value	P-value
Longitudinal sub-model	Intercept	6.54	0.29	22.34	<0.0001
	Time (months)	-0.030	0.0075	-4.04	0.0001
	Age	0.122	0.033	3.68	0.0002
	Female vs Male	-0.666	0.244	-2.73	0.0060
Survival sub-model	Age	-0.045	0.026	-1.75	0.080
	Female vs Male	0.044	0.188	0.24	0.810
Association parameter	γ (gamma)	-0.196	0.049	-4.02	0.0001
Random effects	Intercept variance	4.562	—	—	—
	Time slope variance	0.0032	—	—	—
	Covariance (Int,Time)	-0.040	—	—	—
	Residual SD (σ)	0.624	—	—	—

In the survival sub-model reported in Table 1, neither age nor sex has a statistically significant effect on survival time ($p > 0.05$). However, the association parameter (γ) is negative and highly significant ($p = 0.0001$), confirming that higher Hb levels are associated with a reduced risk of death.

Table 2: Performance criteria for the Joint Model (EM algorithm).

Criterion	AIC	RMSE
Joint Model (EM)	5119.95	0.488

As indicated in Table 2, the Akaike Information Criterion (AIC = 5119.95) reflects a good balance between model fit and complexity, while the relatively low RMSE value (0.488) demonstrates good agreement between the observed and predicted values, confirming the efficiency of the EM-based joint model.

6 CONCLUSIONS

The results of this study demonstrate that the joint model for longitudinal and survival data provides a reliable and effective framework for analyzing the relationship between time-varying biomarkers and survival probabilities in children with leukemia. The longitudinal analysis showed a gradual decline in hemoglobin (Hb) levels over time, reflecting disease progression and treatment effects. Age was positively associated with Hb levels, while females had lower Hb values than males, possibly due to physiological or therapeutic differences.

In the survival analysis, neither age nor sex had a significant direct effect on survival time, suggesting that other clinical or genetic factors may play a stronger role. The association parameter (γ) showed a negative and highly significant relationship, indicating that lower Hb levels increase the risk of death, confirming the predictive power of longitudinal biomarkers in survival estimation.

Performance evaluation criteria demonstrated the efficiency of the Expectation–Maximization (EM) algorithm in providing accurate and stable parameter estimates, even with incomplete data. Overall, the joint model serves as a valuable statistical tool that supports dynamic disease monitoring, enhances prediction accuracy, and aids in evidence-based medical decisions to improve outcomes for children with leukemia.

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Robust and Nonparametric Estimation of the Pareto Reliability Function

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Abstract: The research addresses the topic of reliability, which is defined as the probability of any component of a system being completed within a specified period of time and under the same conditions. The reliability function and failure function of the Pareto distribution were studied. Several methods exist for estimating the reliability function, but the conditions for most of these methods are often missing in the data, such as abnormal, extreme, or unacceptable values. Two estimation methods (a robust method and a nonparametric method) were used: the MM-estimate and the nonparametric kernel estimation. After these two estimation formulas were derived to reach their capacity, a comparison was made between these estimates using simulation experiments with different sample sizes (10, 30 and 60). Each experiment was repeated 1,000 times to achieve the objective, and the results were compared using the mean square error (MSE) criterion. Through the results obtained, it was found that the best estimation method is the (MM-estimate) method, where it was estimated that the reliability function gradually decreases with time, which is consistent with the characteristics of this function.

1 PARETO DISTRIBUTION

This distribution is attributed to the Swiss-born Italian economist Vilfredo Pareto (1848–1923), who laid the foundations of the Pareto distribution in economics by studying the distribution of incomes exceeding a known threshold k. The general Pareto distribution, sometimes called the first or traditional Pareto distribution, has important applications in economics, communications, and various engineering sciences [1], [2].

It is assumed that (x_1, x_2) follow a Pareto distribution with parameters (α_i, k_i), where $i = 1,2$, α_i is the shape parameter, and k_i is the scale parameter, sometimes interpreted as the minimum value. These parameters are then used to compute the reliability estimator $\hat{R}$.

The true reliability R and the reliability estimator $\hat{R}$ are calculated using the robust MM-estimation method and the non-parametric kernel estimation method. Specifically, given values for the shape parameters α_i and scale parameters k_i, these parameters are estimated using the methods above, and the resulting estimates are substituted to compute $\hat{R}$ [3], [4].

2 RELIABILITY

In the concept of globalization, in the recent decades the world has witnessed openness in many fields and the accompanying liberalization of global trade. This competition supposes entry into global markets to attract foreign investment. Meanwhile, the developing countries found themselves in an unenviable position, either trying to join the developed countries in various ways or delaying. So it will be necessary to pay attention to the issues of reliability of the industrial products of all kinds in order to be able to survive and compete in the markets. Because of the importance of reliability and its applications, researchers are directed to study the failure times and reliability of most continuous distributions with the continuation of the modern development. A group of distributions appeared which are called the compounding probability distributions which were received wide attention by

many researchers for their use in many fields, especially in reliability. The compounding probability distributions are one of the failure models that investigate the performance of the work of complex systems and devices. The interest has increased in estimating the reliability function of these distributions. This is to know the operational life of a number of machines and equipment by representing them with one function and to know the efficiency of these machines then evaluate them [5], [6].

2.1 The Reliability of Pareto Distribution

The probability density functions (p.d.f.) of the Pareto distribution for both stress and strength variables can be written as: [7], [8]:

$$f(x_i,\alpha_i,k_i)=\begin{cases}\dfrac{\alpha_i k_i^{\alpha_i}}{x^{\alpha_i+1}} & x_i>k_i \quad , \quad k_i>0 \\ & \alpha_i>0 \quad , \quad i=1,2 \\ 0 & \text{o.w}\end{cases} \tag{1}$$

Since: α_i shape parameter and k_i scale parameter. The cumulative density function (c.d.f.) can be found:

$$F_i(x_i)=1-R_i(x_i) \tag{2}$$

$$F_i(x_i)=1-\left(\frac{k_i}{x_i}\right)^{\alpha i}, \tag{3}$$

$$i=1,2 \quad , \quad x_i \geq k_i>0 \quad , \quad \alpha_i>0$$

The reliability function (R) for stress and toughness is:

$$R=\int_{-\infty}^{\infty} F_2(x_2)\ f_1(x_1).dx$$

$$R=\int_{\max\{k_1,k_2\}}^{\infty}\left\{1-\left(\frac{k_2}{x_2}\right)^{\alpha_2}\right\}\ .\ \left\{\frac{\alpha_1 k_1^{\alpha_1}}{x_1^{\alpha_1+1}}\right\}\ dx \tag{4}$$

$$R=1-\frac{\alpha_1}{\alpha_1+\alpha_2}\left\{\frac{k_2}{\max\{k_1,k_2\}}\right\}^{\alpha_2}\left\{\frac{k_1}{\max\{k_1,k_2\}}\right\}.^{\alpha_1} \tag{5}$$

If the random variables of stress and strength have the same minimum, i.e. k1 = k2, then the reliability (R) in this case is [8], [9]:

$$R=\frac{\alpha_2}{\alpha_1+\alpha_2}. \tag{6}$$

2.2 Estimation Methods

2.2.1 The Robust M.M. Estimation Methods Method

This method is called Robust White. The idea behind this method is to minimize the sum of squared errors to the smallest possible extent, [5], [10], [11]:

$$\min_{a,b}\sum_{i=1}^{n}[Y_i-\beta_0-\beta_1X_i]^2. \tag{7}$$

What the MM-estimate method uses is to minimize the following:

- P is a convex and symmetric function. To obtain robust properties and minimize the above (the sum of squared errors), we use partial derivatives of the coefficients and set them equal to zero.

$$\left.\begin{aligned}\sum_{i=1}^{n}\theta(Y_i-\beta_0-\beta_1X_i)=0\\ \sum_{i=1}^{n}\theta(Y_i-\beta_0-\beta_1X_i)X_i=0\end{aligned}\right\}. \tag{8}$$

- θ is the result of the partial derivative of the above function for the parameters. To obtain the solution to (8), several methods can be used, including mathematical and numerical methods such as the Newton-Raphson method, or by relying on the iteratively weighted partial least squares (IWLS) method as follows:

$$\hat{\beta}_{Rob}=\begin{bmatrix}\beta_0\\ \beta_1\end{bmatrix}=(X^TWX)^{-1}X^TWY.$$

Note that W represents a diagonal weight matrix, and its components can be found as follows:

$$W_{ij}=\frac{\theta\,(Y_i-\beta_0^{\ *}-\beta_1^{\ *}X_i)}{Y_i-\beta_0^{\ \circ}-\beta_1^{\ \circ}X_i}, \tag{9}$$

weights through formula (9) to obtain new values for the first iteration. And then the values are in advance in the calculation and continue to repeat until we get the values of bw very close to each other in successive frequencies are stopped and the last estimate of the formula (10) is the estimate of MM [12], [13].

Since the MM estimator has a constant property, (7) can be expressed as follows. Therefore, the formula for the equation shown in (8) is as follows:

$$\left.\begin{aligned}\sum_{i=1}^{n}\theta\left(\frac{Y_i-\beta_0-\beta_1X_i}{\hat{\delta}}\right)=0\\ \sum_{i=1}^{n}\theta\left(\frac{Y_i-\beta_0-\beta_1X_i}{\hat{\delta}}\right)X_i=0\end{aligned}\right\}. \quad (10)$$

Therefore, the weight matrix functions W are written as in (12) as follows:

$$W_{ij}=\frac{\theta\left(\frac{Y_i-\beta_0{}^{*}-\beta_1{}^{*}X_i}{\hat{\delta}}\right)}{\left(\frac{Y_i-\beta_0{}^{\circ}-\beta_1{}^{\circ}X_i}{\hat{\delta}}\right)}. \quad (11)$$

Estimating formulas for standard deviation values that are pre-determined before the iteration begins using one of the following formulas:

$$\begin{aligned}&1)\ \hat{\delta}=2.1\ \text{Med}\ |u_i|\\ &2)\ \hat{\delta}=\frac{1}{n-4}\sum_{i=3}^{n-2}|u_i|\\ &3)\ \hat{\delta}=1.48\ \text{Med}\ |u_i|\\ &4)\ \text{Med}\ |u_i|/0.6745\end{aligned}. \quad (12)$$

where: $u_i = Y_i-\beta_0-\beta_1X_i$,

Where u_i represents the errors, and represents the ordered errors calculated as follows: As a result of the increasing interest in this method (estimator) over the past decades, many interested parties and researchers have used the method of robust estimators such as (Rews, Hinnich, Hameich, and Talwar) to propose many functions. This is to produce an insensitive and ineffective estimator. Some of these functions can be illustrated in the following table [14], [15], Table 1.

Table 1: Some functions are proposed as weights for fortified estimates.

Weight function	P(e)	W(e)	ψ(e)	Range
A	A^2[1-cos(e/A)]	(u/A)-1 sin(e/A)	A sin (e/A)	|e|≤Aπ
	$2A^2$	0	0	|e|>Aπ
B	$(B^2/2)$[1-$(e/B)^2]^3$	[1-$(e/B)^2]^2$	u [1-$(e/B)^2]^2$	|e|≤B
	$B^2/2$	0	0	|e|>B
T	$e^2/2$	1	u	|e|≤T
	$T^2/2$	0	0	|e|>T
H	$e^2/2$	1	u	|e|≤H
	H	H(e)-1	Sin (e)H	|e|>H

- e: Is the error to be underestimated and in our search, this is a model error in (14);
- P(e): Function in terms of variable e;
- ψ (e): A weight function designed to reduce error;
- W (e): The weight matrix used to obtain the estimates has the least error.

The constants specified in the "Range" column are used to adjust the efficiency of the resulting capacities and take the values shown in the following.

The constants specified in the “Range” column are used to adjust the efficiency of the resulting amplitudes and take the values shown in the following Table 2.

Table 2: Matrix of weights used to obtain estimates has the least error.

Weight function	T	A	B	H
Fixed parts	2.795	1.339	4.685	1.345

The MM distribution is a normal distribution of mean and variance matrix according to the following formula:

$$\text{Var}-\text{Cov}(\hat{\beta}_{\text{Rob}})=\sigma^2_{\text{Rob}}\,(X^TX)^{-1}. \quad (13)$$

And to appreciate it comes as follows:

$$\sigma^2_{\text{Rob}}=\frac{E(\theta^2)}{[E(\theta')]^2}. \quad (14)$$

And to be appreciated, σ^2_{Rob} it comes as:

$$\sigma^2_{\text{Rob}}=\frac{\frac{1}{n}\sum_{i=1}^{n}\theta^2\,(r_i)}{\left[\frac{1}{n}\sum_{i=1}^{n}\theta'\,(u_i)\right]^2}. \quad (15)$$

where σ^2_{Rob} is a biased estimate and to make it an unbiased estimate is based on the following formula:

$$\sigma^2_{\text{Rob}}=R^2\frac{\frac{1}{n-\rho}\sum_{i=1}^{n}\theta^2\,(r_i)}{\left[\frac{1}{n}\sum_{i=1}^{n}\theta'\,(r_i)\right]^2}. \quad (16)$$

Where R represents the correction coefficient and is calculated as follows:

$$R=1+\frac{\rho\ \text{Var}\,(\theta')}{n\,[E(\theta')]^2}. \quad (17)$$

After obtaining the MM estimator for the model parameters i.e:

$$\hat{Y}_i=\hat{\beta}_0+\hat{\beta}_1X_i. \quad (18)$$

The estimate for the distribution of pareto for this method is:

$$F_i(x_i) = 1 - \left(\frac{v_i}{x_i}\right)^{\alpha i}, \quad (19)$$

$$1 - F_i(x_i) = \left(\frac{v_i}{x_i}\right)^{\alpha i},$$

$$\ln(1 - F_i(x_i)) = \alpha i \ln v_i - \alpha i \ln X_i,$$

$$\hat{\alpha}i = \hat{\beta}_1 \text{ and } \hat{v}_i = \exp(\hat{\beta}_0/\hat{\beta}_1), \quad (20)$$

obtaining the MM estimator for the reliability function $\hat{R}_{Rob}$, through the following formula:

$$\hat{R}_{Rob} = 1 - \frac{\hat{\alpha}_1}{\hat{\alpha}_1 + \hat{\alpha}_2}\left\{\frac{\hat{v}_2}{\max\{\hat{v}_1, \hat{v}_2\}}\right\}^{\hat{\alpha}_2}\left\{\frac{\hat{v}_1}{\max\{\hat{v}_1, \hat{v}_2\}}\right\}^{\hat{\alpha}_1}. \quad (21)$$

2.2.2 Kernel Estimation Method (K.E)

This method (kernel estimation) is a scientific method for estimation clustering, agency, death, spectrum, decoration, etc. It was proposed by Barrissen and is intended to purify data by constructing capabilities with properties that match the actual parameters. There are different types of kernel estimation [16].

$$K(x) = \frac{1}{\sqrt{2\,\pi}} \exp\left(\frac{-y^2}{2}\right) \quad 0 \le y \le 1. \quad (22)$$

Although the kernel, the task of obtaining capabilities related to the characteristics of statistical research, the researcher (SAR) reiterated that choosing the dollar is not the most important step in the estimation method, rather choosing the value-added factor (H) (bandwidth bandwidth) is the most important, that is, choosing the value-added factor (1), the same requires choosing the value-added factor (h), as this factor greatly affects the bias and variance, and increasing the value-added factor leads to increased bias and reduced shrinkage and vice versa, and as a result, the prevention of value-added is determined at the degree of smoothing the curve. estimated and approaching the true curve, so the following conditions must be verified (h = 0; nh = ∞).

The value-added factor of the kernel can be fixed or change. The firmware is the use of the prime parameter along the real line used to provide the operating function and is estimated according to one of the posterior estimation methods. Ultimately it means using different values of the band and the real line in estimating the deterministic function in some cases where it becomes useful to use the fixed initial parameter and estimate that modify the appropriate sub parameters.

2.2.3 Fixed Bandwidth Kernel Estimation Method (K.F)

Suppose that T1, T2,..., TN is a sample of independent and vulnerable excellent distribution with the prosperous function and knows as follows:

$$\hat{f}_{(K.F)}(t) = \frac{1}{hn}\sum_{i=1}^{n} K\left(\frac{T_i - t}{h}\right), \quad (23)$$

$i = 1,2,\ldots n$

- K: The Kernel and the calculator of the equation of the No. (23), a specific and continuous and similar persistent functionality, has many labels, including a function (weight, format, essential) and in the following conditions [17], [18]:

$$\int_{-\infty}^{\infty} K(x)dx = 1,$$
$$\int_{-\infty}^{\infty} xK(x)dx = 0, \quad (24)$$
$$\int_{-\infty}^{\infty} x^2K(x)dx > 0,$$

- T: represents the time of the estimation of the function of the functionality;
- n: The size of the sample is a predator (Bandwidth), fixed and estimated by the following steps;
- h: recognized fixed preparatory parameter $(\hat{h} = 1.06\,\hat{\delta}n^{-0.2})$.

The standard deviation of the sample and D difference between the normal natural quantile (valunt).

$$\hat{\delta} = \min\left[S, \frac{\hat{D}}{1.349}\right], \quad (25)$$

$$\hat{D} = X_{(0.25n)} - X_{(0.75n)}. \quad (26)$$

which we must receive the Kernel and its own, we can get the assessment of the Kernel and Kalati function:

$$\hat{F}_{(K.f)}(t) = \frac{1}{hn}\sum_{i=1}^{n}\int_{\infty}^{t} K\left(\frac{X - T_i}{h}\right)dX. \quad (27)$$

Thus, the kernel estimate for the reliability function is given by:

$$\widehat{R}_{(K.F)}(t) = 1 - \left[\frac{1}{hn}\sum_{i=1}^{n}\int_{-\infty}^{t} K\left(\frac{X - T_i}{h}\right) dx\right]. \quad (28)$$

That: RK.FT Recruitment of the Proper Museum for Kernel with the Pre-Framework Practice. After the estimate of the function of the Authority by the distance that is the vulnerability of the victory, and we must compare them through the results and find out what is the perfect way or better in terms of practical application. Here they will be beaded by the modalities of estimate of the estimate, and the accuracy of the appreciation methods The accuracy of the appropriate nuclear standard: The comparison measurement for the best way:

Average error box (MSE): Where the scale is a divortiality measure of comparison between the following as the next formula

$$MSE\left(\widehat{R}_{(K.F)}(t)\right) = \frac{1}{r}\sum_{i=1}^{r}\left(\widehat{R}_{(t)} - R_{(t)}\right)^2. \quad (29)$$

Where r: represents the number of replicates per experiment.

3 STAGES OF SIMULATION

The application simulation software (R) was written and implemented on the electronic calculator, and the following steps are the steps of the simulation algorithm.

The first stage: This is the main stage upon which the steps and procedures of the program depend.

First, different default values were selected for the parameters $((\alpha_i, k_i))$. Sixteen cases were identified in Table 3.

Table 3: Represents the default values of the parameter.

Model	α	K
1	0.6	0.8
2	1.2	1.7

Second: Two sizes were selected for different samples: n=10, 30

The second stage: At this stage random observations (data) are generated by the reverse conversion method and according to the parameterized rally distribution as follows [19], [20]:

First: Generate random numbers Ui tracking the regular distribution within the period (0, t)

$$U_i \sim U_{(0,1)} \ , i = 1,2, \dots, n.$$

It represents a continuouus random variable genearated using the electronic calculator acording to the following formula:

$$U = RND(1)$$

Second: The conversion of the data generated from step (1), which follows the regular distribution to the distribution of the railly by a parameters using the distribution function of the ralily distribution and according to the inverse method of conversion:

$$F_i(x_i) = 1 - \left(\frac{k_i}{y_i}\right)^{\alpha_i},$$

$$\text{Then } U = 1 - \left(\frac{k_i}{y_i}\right)^{\alpha_i}.$$

The function cumulative probability function for the distribution of a rally with a parameter, which we conclude: $\left(\frac{k_i}{y_i}\right)^{\alpha_i} = 1 - U$

Taking into consideration the logarithm of the parties we get:

$$y_i = \exp\left[\frac{\alpha_i \ln k_i - \ln(1-u)}{\alpha_i}\right],$$

third level: At this stage, parameters are estimated for the distribution of a parameterized rally using one of the following methods:

Method (Determined MM): In this method, the parameters of the measurement parameters is obtained and according to the formula (9), the parameter of the measurement parameters is obtained.

The fourth stage: At this stage, the reliability function is estimation as one of the concrete and non-scientific methods according to the following estimation methods.

Level five: Repeat this process for 1000 times.

Sixth stage: At this stage, it is possible to compare the quantities obtained for the distribution of the rally with the parameters and its reliability function using the following statistical criteria Average error boxes (MSE) for the reliability function.

4 DISCUSS SIMULATION RESULTS

In this section, the results of simulation experiments will be presented and analyzed to estimate the reliability function according to the solid and non-scientific methods described in the theoretical side of this research. The results shown in the tables will be analyzed in sequence and as follows:

First: To estimate the parameter for the distribution of a parameterized rally by using one of the robust methods, the sample sizes used and the different cases of the initial values shown in Table 4

and to test the number of replicates 1000 described in the tables above.

Second: The results of the statistical standard Mean error squares (MSE) for the estimated parameters of the distributed rally of all the methods and the different sample sizes and all the cases of the initial default values and the experiment of the number of replicates 1000 as shown in the tables below - Tables 4 and 5.

Thirdly, the relability function is estimation by means of the methods and the number of replicates. The results are presented in tables (4 and 5).

The results of Tables 4-5 showed that the MM-Method is the best method of estimation because it possesses the lowest MSE and percentages according to its preference sequence.

Table 4: Represents the mean square error values at a sample size of (10) and the parameter values ($\alpha = 0.6, K = 0.8$).

n	x	Rel (R(t))	MM-E	K-E
10	0.0452	0.9932	0.9903	0.9993
	0.1028	0.9853	0.9840	0.9922
	0.1281	0.9701	0.9758	0.9864
	0.2892	0.9632	0.9633	0.9705
	0.3192	0.9588	0.9536	0.9657
	0.4475	0.9532	0.9518	0.9605
	0.5111	0.9465	0.9474	0.9573
	0.6654	0.9398	0.9345	0.9443
	0.7980	0.9287	0.9265	0.9329
	0.9043	0.9150	0.9143	0.9275
MSE			0.0041	0.0048

Table 5: Represents the mean square error values at a sample size of (30) and the parameter values ($\alpha = 0.6, K = 0.8$).

n	x	Rel (R(t))	MM-E	K-E
30	0.0482	0.9902	0.9932	0.9962
	0.1022	0.9854	0.9860	0.9870
	0.2392	0.9653	0.9648	0.9731
	0.3694	0.9267	0.9318	0.9469
	0.4403	0.9032	0.9140	0.9288
	0.5930	0.8946	0.9027	0.9119
	0.6823	0.8794	0.8756	0.8947
	0.7382	0.8370	0.8445	0.8608
	0.8293	0.8195	0.8200	0.8325
	0.9011	0.7788	0.8032	0.8159
MSE			0.0036	0.0041

The results in the Tables 4,5 and 6 in the case of the assumed parameters (0.6 and 0.8) and the size of the sample (10,30 and 60) in the preferred views of the MM (Robust) method were indicated by the mean error value (MSE) of the table above as the lowest line rate.

Table 6: Represents the mean square error values at a sample size of (60) and the parameter values ($\alpha = 0.6, K = 0.8$).

n	x	Rel (R(t))	MM-E	K-E
60	0.0366	0.9254	0.9931	0.9859
	0.0978	0.9037	0.9472	0.9375
	0.1368	0.8945	0.9162	0.9047
	0.2658	0.8174	0.8936	0.8994
	0.3266	0.8004	0.8273	0.8583
	0.4002	0.7837	0.7829	0.8026
	0.5894	0.7801	0.7284	0.7482
	0.6728	0.6823	0.6296	0.7037
	0.8032	0.6173	0.5782	0.6285
	0.9467	0.5897	0.4829	0.5583
MSE			0.0028	0.0037

Table 7 represents the mean square error values at a sample size of (10) and the parameter values ($\alpha = 1.2, K = 1.7$).

n	x	Rel (R(t))	MM-E	K-E
10	0.2030	0.95145	0.9556	0.92
	0.2316	0.9427	0.9422	0.9198
	0.3679	0.9341	0.9346	0.9108
	0.4350	0.9255	0.9254	0.9016
	0.4957	0.9169	0.9162	0.9124
	0.5545	0.9084	0.9088	0.9054
	0.6636	0.9000	0.9006	0.8924
	0.6757	0.8916	0.8914	0.8804
	0.6836	0.8832	0.8836	0.8586
	0.7437	0.8749	0.8744	0.8724
MSE			0.0172	0.0183

Table 8: Represents the mean square error values at a sample size of (30) and the parameter values ($\alpha = 1.2, K = 1.7$).

n	X	Rel (R(t))	MM-E	K-E
30	0.1984	0.9040	0.9038	0.9199
	0.2504	0.8874	0.8870	0.9196
	0.3888	0.8707	0.8709	0.9132
	0.4126	0.8547	0.8535	0.8908
	0.5172	0.8379	0.8371	0.8806
	0.5346	0.8222	0.8212	0.8595
	0.6488	0.8060	0.8056	0.8123
	0.7048	0.7895	0.7886	0.8063
	0.7986	0.7728	0.7716	0.7936
	0.8708	0.7563	0.7550	0.7845
MSE			0.0096	0.0147

The results in the Tables 7, 8 and 9 in the case of the assumed parameters (1.2 and 1.7) and the size of the sample (10,30 and 60) in the preferred views of the MM (Robust) method were indicated by the mean error value (MSE) of the table above as the lowest line rate.

Table 9: Represents the mean square error values at a sample size of (60) and the parameter values ($\alpha = 1.2, K = 1.7$).

n	X	Rel (R(t))	MM-E	K-E
60	0.1583	0.9157	0.8996	0.9156
	0.1958	0.8749	0.8376	0.8438
	0.2637	0.8269	0.8167	0.8367
	0.3187	0.8033	0.7945	0.8033
	0.4008	0.7835	0.7583	0.7845
	0.4793	0.7265	0.7361	0.7558
	0.5527	0.6824	0.7022	0.7255
	0.6389	0.6278	0.6835	0.7026
	0.7278	0.5828	0.6277	0.6849
	0.8160	0.5274	0.5728	0.6187
MSE			0.0074	0.0117

5 CONCLUSIONS

The results demonstrate that the robust MM method consistently outperforms the non-parametric kernel estimation method, as indicated by the mean square error (MSE) analysis. The observed decrease in MSE values highlights the method's robustness in handling contaminated observations and its ability to accurately capture the underlying phenomenon. Moreover, the convergence of estimates from different methods with increasing sample size aligns with statistical theory, confirming the reliability of the proposed estimators. Applying these methods to other probability distributions in reliability studies may further validate their effectiveness. The simulations also show that the reliability function decreases with increasing operating time, remaining within the expected range [0,1], consistent with the theoretical properties of reliability. These findings suggest that future research could focus on estimating the reliability function for the Pareto distribution using monitoring data of both types, extending the applicability of the proposed methods.

6 RECOMMENDATIONS AND SUGGESTIONS

Hybrid algorithms that combine robust and nonparametric methods could be developed to further reduce estimation error, and the study could be extended to other probability distributions commonly used in reliability analysis, such as Weibull, Exponential, and Lognormal, to evaluate the performance and potential superiority of the MM method in different contexts. The results indicate that estimation accuracy improves with larger sample sizes; therefore, researchers and engineers are encouraged to collect sufficient data to obtain more stable and reliable results. Additionally, future research could explore the use of the truncated Pareto distribution from above as a model for failure, employing simulation methods to compare the effectiveness of various estimation approaches in this scenario.

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Parameter Estimation of the Semicircular Lomax Distribution

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Keywords: Inverse Stereographic Projection, Stereographic Semicircular Lomax Distribution, Survival Function, Cramer Von Mises Method.

Abstract: This study aims to convert a traditional Lomax distribution into the Stereographically Projected Semicircular Lomax (SSL) distribution by making use of the inverse stereographic projection. The main focus is to semicircularize gathering of data from various applied disciplines to impart flexibility at a higher operational level and, therefore, allow appropriate estimation to be carried out through a flexible model for parameters related to SSL distribution. Further, the entire collection of statistical properties of the proposed distribution has been completely laid out from first principles, including those for the CDF, survival function S(t), and the hazard rate function h(t) in addition to the PDF. There have been two methods adopted for the parameter estimation: Maximum Likelihood Estimation and Cramér von Mises methods. Monte Carlo simulation studies were employed in which several fixed sample sizes were considered in order to analyze the performance of the MLE and CVM methods of parameter estimation. The comparison has been made under the Mean Squared Error (MSE) criterion. The results disclosed that MLE does better than CVM in giving smaller MSE values and hence for estimation.

1 INTRODUCTION

Circular data is crucial since natural and social phenomena during which cyclic repetition is involved are researched. Such data could be measured along axes that involve angles, directions, or positions along circles or semicircles. Hence, for example, one may consider wind direction or phenomenal geographic paths.

Such data have completely different statistical properties as compared to the traditional linear data, as the values are constrained in a closed interval normally taken as $(0, 2\pi)$ depending on the nature of the phenomenon under research. Linear distributions may not be suitable to analyze circular data because of the specific structure that circular data have. In modeling such data, special distributions must be considered since they correspond to the circular nature of the data.

One special subclass lying within the semicircle of the unit circle is known as semi-circular data restricted to the interval $(0, \pi)$. To cater for this issue, the Semi-Circular Lomax Distribution has been put forward. It finds applications in economic modeling and is defined in the interval $(0, \pi)$. Nevertheless, its classical linear approach is generally inappropriate for data with circular or semi-circular characteristics.

This motivated the use of transformation techniques such as the Inverse Stereographic Projection to develop new, more flexible semi-circular distributions suited to this type of data. The primary objective behind developing such a new distribution is to integrate the properties of the Lomax distribution with circular transformation methods, allowing for enhanced applications in risk analysis, prediction, and the research of relationships among periodic variables.

Moreover, this approach helps bridge the methodological gap caused by the limitations of classical linear distributions in handling circular or semi-circular data. Several relevant studies have contributed to this area of research:

- Byoung and his colleagues provided a set of semicircular Laplace distributions in 2008 to enable one to fit particular data sets by simple projection [1].
- In the year 2014, Girija et al. formulated the Double Exponential Semi-Circular Distribution using stereographic projection methods [2].

- In 2019, Yedlapalli and collaborators proposed the Stereographic Semi-Circular Lindley Distribution [3].
- In 2022, Ayesha Iftikhar introduced the Modified Third Burr-III(hcMB-III) Stereographic Semi-Circular Distribution [4].
- In 2024, Oleiwi et al. introduced the Stereographic Semi-Circular Rayleigh Distribution [5].

Building on these three attempts, there is a semi-circular model- Stereographically Projected Semicircular Lomax Distribution which results from the application of inverse stereographic projection to the traditional Lomax distribution. Using varying parameter values, the probability density function (PDF) and cumulative distribution function (CDF) were plotted using the proposed distribution. The first two trigonometric moments were then computed in order to investigate the statistical properties of the new model.

2 INVERSE STEREOGRAPHIC PROJECTION METHOD

One of the critical methods transferred by inverse stereographic projection is that continuous distributions defined on the real number line are transformed into distributions defined on the circumference of the unit circle. The angular domain created by this transformation does not cover the entire circular range but is restricted to an open semicircle. In turn, the resulting distribution does not possess complete rotational symmetry.

The limitation has been discussed in past literature, including those by Yedlapalli, and Radhika [6], [7] and another study by Srinivas, Phani, and Girija (2019), which focused on how the limited angular coverage affects circular data modeling.

The Inverse Stereographic Projection is defined as follows:

$$T(\theta) = x = v\tan\left(\frac{\theta}{2}\right). \quad x \in (-\infty, \infty), \theta \in (-\pi, \pi), v > 0, \tag{1}$$

And then

$$\theta = 2\tan^{-1}\left(\frac{x}{v}\right). \tag{2}$$

The CDF of the semicircular distribution is given by

$$G(\theta) = F(x) = F\left(v\tan\left(\frac{\theta}{2}\right)\right), \tag{3}$$

$$g(\theta) = \frac{v}{2} f\left(v\tan\left(\frac{\theta}{2}\right)\right) sec^2\left(\frac{\theta}{2}\right). \tag{4}$$

The method discussed here views the inverse stereographic projection as applied to a probability distribution in order to produce a new semicircular distribution on the interval (0, π) which could be conveniently used for modeling semicircular data.

3 THE SEMICIRCULAR LOMAX DISTRIBUTION (SSL)

This segment introduces another member of the family of transformations of the semicircular distributions, such as the semicircular lomax distribution under stereographic projections. Definition: We say that a random variable X in the real line is lomax distributed with scale parameter α>0, and location parameter λ>0, if its probability density function and cumulative distribution functions of X are respectively given by [8]:

$$f(x, \alpha, \lambda) = \frac{\alpha}{\lambda}\left(1 + \frac{x}{\lambda}\right)^{-(\alpha+1)}, \tag{5}$$

where x>0 and

$$F(x, \alpha, \lambda) = 1 - \left(1 + \frac{x}{\lambda}\right)^{-\alpha}. \tag{6}$$

3.1 The PDF and CDF of SSL Distribution

Note [6] that the Probability Density Functions and Cumulative Distribution Functions corresponding to the Stereographically Projected Semicircular Lomax Distribution can be respectively written as:

$$g(\theta) = \frac{v}{2}\frac{\alpha}{\lambda}\left(1 + \frac{v\tan\left(\frac{\theta}{2}\right)}{\lambda}\right)^{-(\alpha+1)} \sec^2\left(\frac{\theta}{2}\right), \tag{7}$$

The shape of the PDF for different parameter values is illustrated in Figure 1.

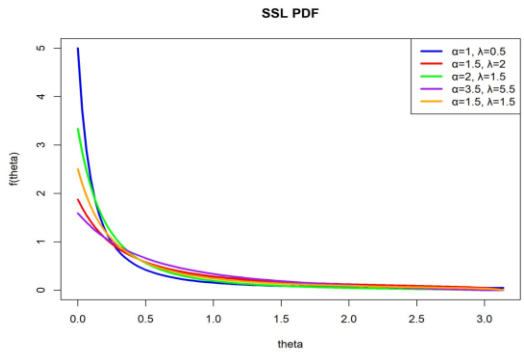


Figure 1: PDF of the Stereographic Lomax distribution.

The CDF of the Stereographically Projected Semicircular Lomax Distribution (SSL), or the nonreliability function, gives the probability that a unit fails before time t. It is defined as:

$$G(\theta,\alpha,\lambda) = 1 - \left(1 + \frac{v\tan\frac{\theta}{2}}{\lambda}\right)^{-\alpha} . \qquad (8)$$

The corresponding CDF curves are shown in Figure 2.

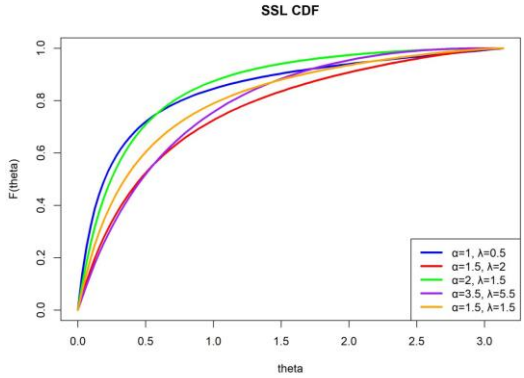


Figure 2: CDF of the Stereographic Lomax distribution.

3.2 Survival Measures and Hazard Function of SSL Distribution

References [9] provide us with the information that from (7) and (8), we can generalize the survival function S(t) and hazard function h(t) for the Stereographically Projected Semicircular Lomax Distribution.

$$S(\theta) = 1 - G(\theta) = \left(1 - \left(1 - \left(1 + \frac{v\tan\frac{\theta}{2}}{\lambda}\right)^{-\alpha}\right)\right).$$

$$S(\theta) = \left(1 + \frac{v\tan\frac{\theta}{2}}{\lambda}\right)^{-\alpha} . \qquad (9)$$

The behavior of the survival function is illustrated in Figure 3.

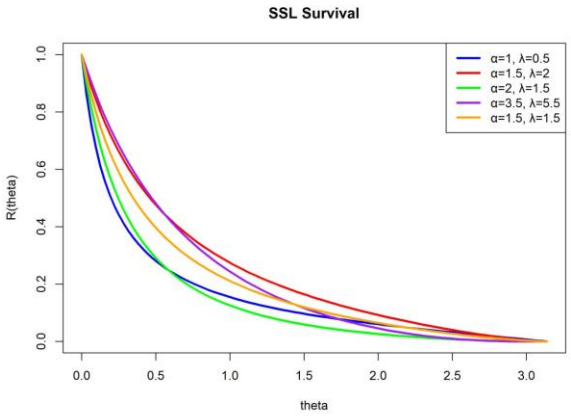


Figure 3: Survival function of the Stereographic Lomax distribution.

$$h(\theta) = \frac{g(\theta)}{1-G(\theta)} = \frac{\frac{v}{2}\frac{\alpha}{\lambda}\left(1+\frac{v\tan\left(\frac{\theta}{2}\right)}{\lambda}\right)^{-(\alpha+1)} sec^2\left(\frac{\theta}{2}\right)}{\left(1+\frac{v\tan\frac{\theta}{2}}{\lambda}\right)^{-\alpha}} \qquad (10)$$

The corresponding hazard function is presented in Figure 4.

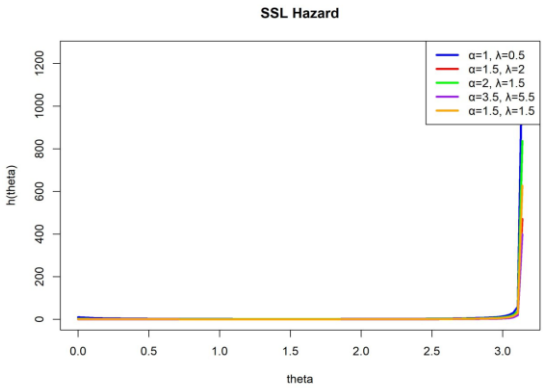


Figure 4: Graph of Hazard function of the Stereographic lomax distribution.

3.3 The r^{th} Moment of *SSL* Distribution

The r^{th} non-central moment of the *SSL* distribution, (θ^{r}) SSL, can be obtained through the pdf in (7) with the following form:

$$E(\theta)^r = \int_0^{\pi} \theta^r \; f(\theta,\alpha,\lambda)\, d\theta \; = \int_0^{\pi} \frac{v}{2}\frac{\alpha}{\lambda}(\theta)^r \left(1 + \frac{vtan\frac{\theta}{2}}{\lambda}\right)^{-(\alpha+1)} \sec^2\tau\left(\frac{\theta}{2}\right) d\theta\,, \qquad (11)$$

$$= \frac{v}{2}\frac{\alpha}{\lambda}\int_0^{\pi}(\theta)^r \left(1 + \frac{vtan\frac{\theta}{2}}{\lambda}\right)^{-(\alpha+1)} \sec^2\left(\frac{\theta}{2}\right) d\theta.$$

Since $x = v\tan\left(\frac{\theta}{2}\right)$, $\theta = 2\tan^{-1}\left(\frac{x}{v}\right)$, $d\theta = \left(\frac{2v}{v^2+x^2}\right) dx$ = $\frac{v}{2}\frac{\alpha}{\lambda}\int_0^{\infty}\left(2\tan^{-1}\left(\frac{x}{v}\right)\right)^r \left(1+\frac{x}{\lambda}\right)^{-(\alpha+1)} \sec^2\left(\frac{2\tan^{-1}\left(\frac{x}{v}\right)}{2}\right)\left(\frac{2v}{v^2+x^2}\right) dx.$

Since $\sec^2\tan^{-1}\left(\frac{x}{v}\right) = \frac{v^2+x^2}{v^2} = \frac{v}{2}\frac{\alpha}{\lambda}\int_0^{\infty}\left(2\tan^{-1}\left(\frac{x}{v}\right)\right)^r \left(1+\frac{x}{\lambda}\right)^{-(\alpha+1)}\left(\frac{v^2+x^2}{v^2}\right)\left(\frac{2v}{v^2+x^2}\right) dx = \frac{\alpha}{\lambda}\int_0^{\infty}\left(2\tan^{-1}\left(\frac{x}{v}\right)\right)^r \left(1+\frac{x}{\lambda}\right)^{-(\alpha+1)} dx.$

Using the power series of $\tan^{-1}(x)$.

$$\text{Let } \tan^{-1} = \sum_{k=0}^{\infty}\frac{(2k)!}{2^{2k}(k!)^2(2k+1)}\left(\frac{\left(\frac{x}{v}\right)^2}{\left(\frac{x}{v}\right)^2+1}\right)^{k+\frac{1}{2}}$$

$$= \frac{\alpha}{\lambda}\int_0^{\infty}\left(2\sum_{k=0}^{\infty}\frac{(2k)!}{2^{2k}(k!)^2(2k+1)}\left(\frac{\left(\frac{x}{v}\right)^2}{\left(\frac{x}{v}\right)^2+1}\right)^{k+\frac{1}{2}}\right)^r \left(1+\frac{x}{\lambda}\right)^{-(\alpha+1)} dx.$$

$$\text{let } u = \frac{\left(\frac{x}{v}\right)^2}{\left(\frac{x}{v}\right)^2+1} \qquad x = v\left(\frac{1}{u}-1\right)^{\frac{-1}{2}}$$

$$dx = \frac{v}{2u^2}\left(\frac{1}{u}-1\right)^{\frac{-3}{2}} du$$

$$= \frac{\alpha}{\lambda}\int_0^1 \left(2\sum_{k=0}^{\infty}\frac{(2k)!}{2^{2k}(k!)^2(2k+1)}\, u^{k+\frac{1}{2}}\right)^r \left(1+\frac{v\left(\frac{1}{u}-1\right)^{\frac{-1}{2}}}{\lambda}\right)^{-(\alpha+1)} \frac{v}{2u^2}\left(\frac{1}{u}-1\right)^{\frac{-3}{2}} du.$$

Using Newton Binomial formula we obtain

$$\left(1+\frac{v\left(\frac{1}{u}-1\right)^{\frac{-1}{2}}}{\lambda}\right)^{-(\alpha+1)} = \sum_{j=0}^{\infty}\binom{-(\alpha+1)}{j}\left(\frac{v}{\lambda}\right)^j \left(\left(\frac{1}{u}-1\right)^{\frac{-1}{2}}\right)^j$$

$$= \frac{\alpha}{\lambda}\int_0^1 \frac{v}{2u^2}\left(2\sum_{k=0}^{\infty}\frac{(2k)!}{2^{2k}(k!)^2(2k+1)}\, u^{k+\frac{1}{2}}\right)\sum_{j=0}^{\infty}\binom{-(\alpha+1)}{j}\left(\frac{v}{\lambda}\right)^j\left(\frac{1}{u}-1\right)^{\frac{-3}{2}-\frac{j}{2}} du\,,$$

$$(1-u)^{\frac{-3}{2}-\frac{j}{2}} = \sum_{m=0}^{\infty}\binom{-\frac{3}{2}-\frac{j}{2}}{m}(-1)^m\left(\frac{1}{u}\right)^{-m}(u)^{\frac{3}{2}+\frac{j}{2}}$$

$$= \frac{\alpha}{\lambda}\int_0^1 \frac{v}{2u^2}\left(2\sum_{k=0}^{\infty}\frac{(2k)!}{2^{2k}(k!)^2(2k+1)}\, u^{k+\frac{1}{2}}\right)^r \sum_{j=0}^{\infty}\sum_{m=0}^{\infty}\binom{-(\alpha+1)}{j}\binom{-\frac{3}{2}-\frac{j}{2}}{m}\left(\frac{v}{\lambda}\right)^j(-1)^m\left(\frac{1}{u}\right)^{\frac{-3}{2}-\frac{j}{2}-m} du$$

$$= \frac{\alpha 2^r}{\lambda}\frac{v}{2}\sum_{j,m=0}^{\infty}\binom{-(\alpha+1)}{j}\left(\frac{v}{\lambda}\right)^j\binom{\frac{-3}{2}-\frac{j}{2}}{m}(-1)^m\int_0^1\left(\sum_{k=0}^{\infty}\frac{(2k)!}{2^{2k}(k!)^2(2k+1)}\, u^k\right)^r (u)^{m+\frac{r}{2}+\frac{3}{2}+\frac{j}{2}-2} du$$

According to the circumstance $\left(\sum_{k=0}^{\infty} a_k\, u^k\right)^r$

$= \sum_{k=0}^{\infty} b_k\,(u)^k$; r is a natural number b_0

$= a_0^r$, and $b_h = \frac{1}{a_0\, h}\sum_{k=1}^{h}(kr-h+k)\; a_k\, b_{h-k}$; h ≥ 1, the $E(\theta)^r$ with

$a_k = \frac{(2k)!}{2^{2k}(k!)^2(2k+1)}$ *will be*

$$E(\theta)^r = \frac{b_k\,\alpha 2^r}{\lambda}\frac{v}{2}\sum_{j,m,k=0}^{\infty}\binom{-(\alpha+1)}{j}\left(\frac{v}{\lambda}\right)^j\binom{\frac{-3}{2}-\frac{j}{2}}{m}(-1)^m\int_0^1 (u)^{k+m+\frac{r}{2}+\frac{j}{2}+\frac{3}{2}-2} du,$$

$$E(\theta)^r = \frac{b_k\,\alpha 2^r}{\lambda}\frac{v}{2}\sum_{j,m,k=0}^{\infty}\binom{-(\alpha+1)}{j}\left(\frac{v}{\lambda}\right)^j\binom{\frac{-3}{2}-\frac{j}{2}}{m}(-1)^m\frac{1}{k+m+\frac{r}{2}+\frac{j}{2}+\frac{3}{2}-1}. \qquad (12)$$

3.4 Trigonometric Moments

To study the population characteristic, the first and second trigonometric moments of the Stereographic semicircular Lomax distribution are derived. The moments of the distribution, being the b^th; b= 0, ±1, ±2…, can be introduced from [3] [10].

$$\emptyset_b = \alpha_b + i\delta_b \quad , \emptyset_b = b, \mp 1, \mp 2 \ldots\ldots$$
$$\alpha_b = E(\cos b\theta)$$
$$\lambda_b = E(\sin b\theta)$$

$$E(\cos b\theta) = \int_0^{\pi}\cos(b\theta)\, f(\theta,\alpha,\lambda)d\theta\,, \qquad (13)$$

$$E(\cos b\theta) = \int_0^{\pi}\cos(b\theta)\frac{v}{2}\frac{\alpha}{\lambda}\left(1+\frac{v\tan\frac{\theta}{2}}{\beta}\right)^{-(\alpha+1)}\sec^2\left(\frac{\theta}{2}\right)d\theta,$$

$$\text{let } \cos(b\theta) = \sum_{n=0}^{\infty}\frac{(-1)^n}{(2n)!}(b\theta)^{2n} = \sum_{n=0}^{\infty}\frac{(-1)^n}{(2n)!}(b)^{2n}(\theta)^{2n},$$

$$E(\cos b\theta) = = \sum_{n=0}^{\infty}\frac{(-1)^n}{(2n)!}(b)^{2n}\int_0^{\pi}(\theta)^{2n}\frac{v}{2}\frac{\alpha}{\lambda}\left(1+\frac{v\tan\frac{\theta}{2}}{\beta}\right)^{-(\alpha+1)}\sec^2\left(\frac{\theta}{2}\right)d\theta,$$

$$E(\cos b\theta) = \sum_{n=0}^{\infty}\frac{(-1)^n}{(2n)!}(b)^{2n}\; E(\theta)^{2n},$$

$$\alpha_1 = \sum_{n=0}^{\infty}\frac{(-1)^n}{(2n)!}(1)^{2n}\, E(\theta)^{2n}, \qquad (14)$$

$$\alpha_2 = \sum_{n=0}^{\infty}\frac{(-1)^n}{(2n)!}(2)^{2n}\, E(\theta)^{2n}, \qquad (15)$$

$$E(\sin b\theta) = \int_0^{\pi} \sin(b\theta)\ \frac{v}{2}\frac{\alpha}{\lambda}\left(1+\frac{vtan\frac{\theta}{2}}{\lambda}\right)^{-(\alpha+1)} \sec^2\left(\frac{\theta}{2}\right) d\theta, \quad (16)$$

$$let \sin(b\theta) = \sum_{n=0}^{\infty}\frac{(-1)^n}{(2n+1)!}(b\theta)^{2n+1} = \sum_{n=0}^{\infty}\frac{(-1)^n}{(2n+1)!}(b)^{2n+1}(\theta)^{2n+1}$$

$$= \sum_{n=0}^{\infty}\frac{(-1)^n}{(2n+1)!}(b)^{2n+1}\int_0^{\pi}(\theta)^{2n+1}\ \frac{v}{2}\frac{\alpha}{\lambda}\left(1+\frac{vtan\frac{\theta}{2}}{\lambda}\right)^{-(\alpha+1)} \sec^2\left(\frac{\theta}{2}\right) d\theta$$

$$E(\sin b\theta) = \sum_{n=0}^{\infty}\frac{(-1)^n}{(2n+1)!}\ (b)^{2n+1}\ E(\theta)^{2n+1}$$

$$\lambda_1 = \sum_{n=0}^{\infty}\frac{(-1)^n}{(2n+1)!}\ (1)^{2n+1}\ E(\theta)^{2n+1}, \quad (17)$$

$$\lambda_2 = \sum_{n=0}^{\infty}\frac{(-1)^n}{(2n+1)!}\ (2)^{2n+1}\ E(\theta)^{2n+1}. \quad (18)$$

Here $(\theta^{2n+1})\ SSl\ and\ \ E(\theta^{2n})SSL$ as in (8) respectively.

With $r = 2n + 1$ and $r = 2n$.

Simulated data and a quantile function for *S*SL distribution. By means of inversion of the cdf in (8), the quantile function of the *S*SL distribution is obtained as in [11].

$$\theta_{(q)SSL} = 2\tan^{-1}\left(\frac{\lambda}{v}\left[(1-u)^{\frac{-1}{\alpha}} - 1\ \right]\right). \quad (19)$$

The median of the SSL random variable can be gained from (20) by setting $q = \frac{1}{2}$ as

$$\theta_{med} = 2\tan^{-1}\left(\frac{\lambda}{v}\left[\left(1-\frac{1}{2}\right)^{\frac{-1}{\alpha}} - 1\ \right]\right). \quad (20)$$

By replacing q with u a random variable that follows *S*SL distribution can be simulated as:

$$\theta_{SSL} = 2\tan^{-1}\left(\frac{\lambda}{v}\left[(1-u)^{\frac{-1}{\alpha}} - 1\ \right]\right), \quad (21)$$

where u is an interval based uniform random number (0,1).

4 ESTIMATION METHODS

4.1 Maximum Likelihood Method

It is a method most often used for estimation because it possesses a set of characteristics that distinguish it from others. These features include consistency, which is mostly present, stability, and unbiasedness [12] - [14].

$$f(\theta,\alpha,\lambda) = \frac{v}{2}\ \frac{\alpha}{\lambda}\left(1+\frac{vtan\frac{\theta}{2}}{\lambda}\right)^{-(\alpha+1)} \quad sec^2\left(\frac{\theta}{2}\right),$$

$$Lf(\theta,\alpha,\lambda) = \prod_{i=1}^{n}\left[\frac{v}{2}\frac{\alpha}{\lambda}\left(1+\frac{vtan\frac{\theta_i}{2}}{\lambda}\right)^{-(\alpha+1)} \quad sec^2\left(\frac{\theta_i}{2}\right)\right],$$

$$= \left(\frac{v}{2}\right)^n\left(\frac{\alpha}{\lambda}\right)^n \prod_{i=1}^{n}\left(1+\frac{vtan\frac{\theta_i}{2}}{\lambda}\right)^{-(\alpha+1)} \quad \prod_{i=1}^{n} sec^2\left(\frac{\theta_i}{2}\right), \quad (22)$$

$$Ln\ L = n\ln v + n\ Ln\ \alpha - n\ Ln2 - n\ Ln\ \lambda - (\alpha+1)\sum_{i=1}^{n} Ln\left(1+\frac{vtan\frac{\theta_i}{2}}{\lambda}\right) + 2\sum_{i=1}^{n} Ln\sec\left(\frac{\theta_i}{2}\right),$$

$$\frac{\partial\ Ln\ L(\alpha,\lambda)}{\partial\alpha} = \frac{n}{\alpha} - \sum_{i=1}^{n} Ln\left(1+\frac{vtan\ \frac{\theta_i}{2}}{\lambda}\right) = 0. \quad (23)$$

The partial derivative with respect to the parameter λ.

$$\frac{\partial Ln\ L(\alpha,\lambda)}{\partial\lambda} = -\frac{n}{\lambda} + (\alpha+1)\sum_{i=1}^{n}\frac{\frac{vtan\frac{\theta_i}{2}}{\lambda^2}}{1+\frac{vtan\frac{\theta_i}{2}}{\lambda}} = 0. \quad (24)$$

4.2 Cramer–von Mises Method

Such a minimum distance estimator constructed from the difference between the theoretical and empirical cumulative distribution functions is realizable as follows: By taking partial derivatives with respect to the parameters and setting the results equal to zero, we find the parameter estimates [15], [16].

$$k(\alpha,\lambda) = \frac{1}{12n} + \sum_{i=1}^{n}\left[F(\theta,\alpha,\lambda) - \frac{2i-1}{2n}\right]^2. \quad (25)$$

$$k(\alpha,\lambda) = \frac{1}{12n} + \sum_{i=1}^{n}\left[1-\left(1+\frac{vtan\frac{\theta}{2}}{\lambda}\right)^{-\alpha} - \frac{2i-1}{2n}\right]^2,$$

$$\frac{\partial\ k}{\partial\ \alpha} = 2\sum_{i=1}^{n}\left[F(\theta,\alpha,\lambda) - \frac{2i-1}{2n}\right]\ \frac{\partial F(\theta,\alpha,\lambda)}{\partial\alpha},$$

$$\frac{\partial k}{\partial\alpha} = 2\sum_{i=1}^{n}\left[1-\left(1+\frac{vtan\frac{\theta}{2}}{\lambda}\right)^{-\alpha} - \frac{2i-1}{2n}\right].\left(1+\frac{vtan\frac{\theta}{2}}{\lambda}\right)^{-\alpha} ln\left(1+\frac{vtan\frac{\theta}{2}}{\lambda}\right) = 0. \quad (26)$$

$$\frac{\partial\ k}{\partial\ \lambda} = 2\sum_{i=1}^{n}\left[F(\theta,\alpha,\lambda) - \frac{2i-1}{2n}\right]\ \frac{\partial F(\theta,\alpha,\lambda)}{\partial\lambda},$$

$$\frac{\partial k}{\partial\lambda} = 2\sum_{i=1}^{n}\left[1-\left(1+\frac{vtan\frac{\theta}{2}}{\lambda}\right)^{-\alpha} - \frac{2i-1}{2n}\right].\alpha\left(1+\frac{vtan\frac{\theta}{2}}{\lambda}\right)^{-\alpha-1}\ \frac{vtan\frac{\theta}{2}}{\lambda^2} = 0. \quad (27)$$

5 SIMULATION STUDY

Empirical behaviors of Maximum likelihood and Cramer–von Mises of the SSL parameters had to be detected at various sample sizes (10, 25, 50, 75, and 100) through simulation studies via R. The SSL value is simulated based on (21) by plugging in the parameters' default values shown in the table, where λ=0.5; α=1; v=1. For the experiment, K=1000. The tests are compared and determined through the use of the mean square error criterion.

$$\mathrm{MSE}(\Omega) = \frac{1}{1000}\sum_{i=1}^{1000}\left(\widehat{\Omega}_i - \Omega\right)^2. \qquad (28)$$

Accordingly, the estimates of the parameters of the semicircular stereographic Lomax distribution resulting from the simulation study using the (MLE) and (CVM) methods are shown in Table 1, and the mean squared error (MSE) values of these estimates are shown in Table 2.

Table 1: The estimated parameter values at the assumed values (α = 1, λ = 0.5).

n	Method	α est.	λ est.
10	MLE	1.21577	0.63889
	CVM	1.11423	0.60357
25	MLE	1.12402	0.60136
	CVM	1.10399	0.59211
50	MLE	1.10891	0.59126
	CVM	1.10164	0.58811
75	MLE	1.07310	0.56215
	CVM	1.08787	0.57085
100	MLE	1.05928	0.54983
	CVM	1.08009	0.56395

Table 2: The MSE values of the parameters at the assumed values (α = 1, λ = 0.5).

n	Method	α MSE	λ MSE.
10	MLE	0.29276	0.13052
	CVM	0.26990	0.13643
25	MLE	0.15802	0.09489
	CVM	0.18548	0.10513
50	MLE	0.11017	0.06915
	CVM	0.14159	0.08352
75	MLE	0.07047	0.04753
	CVM	0.11346	0.06440
100	MLE	0.05437	0.03830
	CVM	0.08901	0.05245

The results of Tables 1 and 2 indicate that the Maximum Likelihood Estimation (MLE) method yields better performance in estimating the parameters (α, λ) compared to the Cramer–von Mises (CVM) method. There are smaller MSEs across smaller to larger sample sizes; hence, this conclusion. The larger the sample size, the smaller the MSE values, which in turn show increasing estimation accuracy; this property is known as consistency.

6 CONCLUSIONS

The Stereographic Semicircular Lomax Distribution (SSL) was introduced through the application of the Inverse Stereographic Projection method. The main contribution of this study is to extend the classical Lomax model to a semicircular framework, which has not been considered in previous studies. The proposed distribution is flexible and capable of handling the varied kinds of semicircular data observed in several fields. The basic statistical properties, including the probability density function and cumulative distribution function, survival function, hazard rate, along with others.

Simulations indicated that the Maximum Likelihood Estimation technique is superior for deriving parameter estimates compared to the Cramer–von Mises approach, particularly as the sample size expands. This conclusion was further substantiated by The MSE values of the MLE estimators are lower compared to the Cramer Von Mises estimators, especially with increasing sample size. Although the study is based on simulated data, the results demonstrate the effectiveness of the proposed distribution in accurately reflecting the statistical behavior of semicircular data. it also confirms its suitability and ability to represent semicircular data.

7 RECOMMENDATIONS

The study therefore suggests that MLE should be central to parameter estimation for any SSL distribution on account of its perceived increased adeptness. Due to the very general capability to model any semi-circular data, the proposed distribution finds application in many areas. The focal points of the coming researchers should be as follows: the complete comparison of the performance of the alternative estimators such as Least Squares or Bayesian Estimation against MLE and CVM methods. It is further strongly recommended to try this distribution on empirical data from practical applications to critically test its practical usefulness.

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Common Correlated Effects Estimation of Hybrid Panel Data Models

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Keywords: Common Correlated Effects, Hybrid Coefficients Model, Unbalanced Panel Data, Mean Group Estimator, Pooled Estimator, Half Jackknife Panel Estimator.

Abstract: In this research, a model of panel data models was reviewed which is hybrid coefficients model which is characterized by a portion of the regression coefficients being fixed slopes while the other portion of the coefficients are random slopes meaning that they have a normal distribution with an unknown mean and variance. Several methods were used to estimate the parameters of this model in the case of unbalanced panel data. these estimation methods depend on the common correlated effects estimator which is composed of three estimators, common correlated effect mean group estimator(CCEMG), common correlated effect pooled (CCEP) and half jackknife panel (HJP)estimator to estimate the parameters of the hybrid coefficients model represented by the first fixed slope and the mean of the random slope coefficient. Monte Carlo experiments and different sample sizes (NT) are small, medium and large, with different variance levels to compare between estimation methods, the simulation results showed that the (CCEP) is the best estimation method because it has the less average mean absolute error (AMAE). The (CCMG) is the best method after (CCEP).

1 INTRODUCTION

Since the beginning of the fifties of the twentieth century, applied studies have taken a new path characterized by the increasing use of theoretical hypotheses that are in the form of primary information derived from outside the scope of the sample and provided by the theory behind the phenomenon studied or previous studies and combining them with sample data whether cross – sectional data or time series data, to obtain estimates of the parameters of the model studied that more efficient than the estimators based on time series or cross sectional alone. methods used to combine time series and cross-sectional data at the single equation level involve using the cross-sectional data to estimate some model parameters and then introducing these estimators as constant value constraints into the time series regression equation.

Panel data consists of cross-sectional data and time series data. the behavior of data categories is observed over a period of time. These categories maybe (countries, companies,…,etc) [1]. Observation from the same category is correlated and correlation is the distinguishing feature of these data. They are also known as longitudinal data. panel data have group effects (cross sectional) or have time effects or both. panel data are divided into two types, balanced panel data which contain equal time periods for all cross sections but if the time period differs across cross sections, it is called unbalanced panel data. the main objective of this research is to estimate the parameters of hybrid coefficients model for unbalanced panel data and to compare the estimation methods to show the best estimation methods.

2 PANEL DATA REGRESSION MODELS

Regression analysis is one of the important topics of statistics, which is widely used in all fields of science and knowledge because it describes the relation between variables in the form of an equation it can be known in general as the analysis that specializes in studying the effect of one or more variables called the independent variable or independent variables on one variable called the dependent variable [2]. This is for the purpose of estimating or predicting the value of the dependent variable given the information of the independent variable or variables.

Accordingly, the regression model is used to arrive at mathematical model that explains the quantitative relationship between the dependent and the independent variables. Therefore, it can be defined as a statistical method used to analyze data that contains two or more variables when the goal is to discover the nature of this relationship.

In general, regression models can be classified according to several factors [3]:

1) The number of the variables. There is common division of regression models according to the number of independent variables used in the models. if the model contains one independent variable with the dependent variable, the model is called a simple regression model. however, if the number of independent variables is more than one, it is called a multiple regression model.
2) The form of the relation between the variables. Here we can distinguish between two types of regression models, the linear regression model and nonlinear regression model.
3) Level of measurement for variables. This classification depends on the type of data for the dependent variable, whether it is descriptive or quantitative data. here, it can be divided in two types of regression models, logistic regression models it is used when the data of the dependent variable is descriptive. the second is the traditional regression model, which is used when the data of the dependent variable is quantitative data. if the quantitative data is time series data, then time series regression models are used, and if the quantitative contains cross sections, then cross – sectional data regression models are used. but if the dependent variable and the independent variables are time series and cross – sectional data, then panel data models are used because the independent variables and the dependent variable have two dimensions, which are the cross – section and time.

In the current decade, panel data models have gained great interest especially in economic and medical studies because they take into account the effect of change in time as well as the effect change in cross – sectional observations. many researchers studied panel data models, some of whom were interested in studying the properties of these models mathematically [4], [5]. Among those who were interested in applying these models in their studies [6], [7].

The panel data has the following properties [1], [8]:

1) it allows controlling individual variation that may appear in the case of cross – sectional or temporal data which leads to biased results;
2) it helps control some variables that remain constant among individuals but change over time, such as national policies and international agreements;
3) panel data contain more information content that cross – sectional or temporal data, and therefore it is possible to obtain estimates with higher confidence and the problem of common correlation between variables is less severe than time series data;
4) panel data distinguished from others in that it includes a greater number of degrees of freedom and is characterized by better efficiency as well as multicollinearity between variables and more information content if cross – sectional or temporal data are used;
5) panel data models provide a better possibility to study the adjustment dynamics that may be hidden by cross – sectional data, and they are also suitable for studying periods of economic conditions such as unemployment poverty, growth and others. on the other hand, it is possible through panel data to link the behaviors of the sample observations from one point in time to another;
6) panel data models contribute to reducing the possibility of the problem of neglected variables resulting from unobserved item characteristics that usually lead to biased estimates;
7) the importance of using panel data is that takes into account what is described as heterogeneity or unobserved difference specifics to the sample observations whether cross – sectional or temporal;
8) these models help prevent the common problem of heteroscedasticity.

3 THE MODEL

In simple and multiple regression model, the regression coefficients are fixed parameters so we seek to estimate these parameters using classical or Bayesian methods [9]. However, when the regression coefficients(slopes) are random parameters and not fixed, then they are called random coefficient (RCR) model [10].

In the research, we will discuss a model that contains both fixed and random regression coefficients, which is given by the following [11]:

$$Y_{it} = X_{1it}\beta_1 + X_{2it}\beta_{2i} + u_{it}, \quad (1)$$

where i=1,2,…,N represent cross section unit and t=1,2,…,T_i represent time series period.

Model (1) is unbalanced panel data, meaning that there are N individuals observed over varying time periods length (i=1,2, …, T_i). the model in (1) can be rewritten by stacking over time period t:

$$Y_i = X_{1i}\beta_1 + X_{2i}\beta_{2i} + u_i, \quad (2)$$

where $Y_i = (Y_{i1}, \dots, Y_{iT_i})'$,$X_{1i}, X_{2i}$ are matrices of rank $T_i \times K_1$ and $T_i \times K_2$ for explanatory variables and $\beta_1$is fixed slope of rank $K_1 \times 1$, β_{2i} is assumed random slope of rank $K_2 \times 1$, finally u_i is the random error of rank $T_i \times 1$. the model (2) has the following assumptions [12]:

Assumption 1: the random error has $E(u_i) = 0$ and $var(u_i) = \sigma_u^2 I_{T_i}$ $i = 1,2, \dots, N$.

Assumption 2: the slope coefficients β_{2i} are independent and distributed with:

$$E(\beta_{2i}) = \bar{\beta}_{2,} var(\beta_{2ij}) = \begin{cases} \Delta & i = j \\ 0 & i \neq j \end{cases} \; i,j = 1, \dots, N.$$

From assumption (2) can be written the random slope [13]:

$$\beta_{2i} = \bar{\beta}_2 + \mu_i, \quad (3)$$

where $\bar{\beta}_2 = (\bar{\beta}_{21}, \dots, \bar{\beta}_{2K_2})'$is a vector of constant parameters and $\mu_i = (\mu_1, \dots, \mu_{K_2})'$ with:

$$E(\mu_i) = 0, var(\mu_{ij}) = \begin{cases} \Delta & i = j \\ 0 & i \neq j \end{cases} \; i,j = 1, \dots, N,$$

where Δ is a K_2 diagonal matrix. we note that the random slope in assumption (3) is constant over time periods but changes over the cross sections due to the change in the random error.

By substituting (3) into (2), we get:

$$Y_i = X_{1i}\beta_1 + X_{2i}\bar{\beta}_2 + \varepsilon_i, \quad (4)$$

where $\varepsilon_i = X_{2i}\mu_i + u_i$, by rewriting the above model, we get:

$$Y = Q\bar{\theta} + \varepsilon, \quad (5)$$

where $Y = (Y_1, \dots, Y_N)', Q = (Q_1', \dots, Q_N')', \bar{\theta} = (\beta_1', \bar{\beta}_2')', Q_i = (X_{1i}, X_{2i}), \varepsilon = (\varepsilon_1', \dots, \varepsilon_2')'$.

4 ESTIMATION

In this section we will use different estimation methods to estimate the parameters of the hybrid coefficients model in the (5). These methods based on CCE estimator and are as follows:

4.1 CCE Mean Group Estimator

The common correlated effect estimator proposed by [14] to estimate panel data model with random regression coefficient. the CCEMG for estimate parameters in model (5) is given by [15]:

$$\hat{\bar{\theta}}_{CCEMG} = \frac{1}{N}\sum_{i=1}^{N} \hat{\theta}_{CCE,i}, \quad (6)$$

where $\hat{\theta}_{CCE,i}$is the (CCE) for each cross – sectional i which equal to:

$$\hat{\theta}_{CCE,i} = (Q_i' M_H Q_i)^{-1} Q_i' M_H Y_i, \quad (7)$$

where:

$$M_H = I_{T_i} - (H'H)^{-1}H',$$
$$H = (\bar{Q}, \bar{Y}),$$
$$\bar{Q} = (\bar{Q}_1, \dots, \bar{Q}_T)', \bar{Y} = (\bar{Y}_1, \dots, \bar{Y}_T),$$
$$\bar{Q}_t = \frac{1}{N}\sum_{i=1}^{N} Q_{it}, \bar{Y}_t = \frac{1}{N}\sum_{i=1}^{N} Y_{it},$$

The (CCEMG) is asymptotically distributed as [10]:

$$\sqrt{N}\left(\hat{\bar{\theta}}_{CCEMG} - \bar{\theta}\right) \rightarrow N(0, \hat{\gamma}_{CCEMG}),$$

where $\hat{\gamma}_{CCEMG}$ the variance of estimator in (6).

4.2 CCE Pooled Estimator

The CCEP estimator is calculated when the individuals slope coefficient β_{2i} are differ from cross–sectional to another. the CCEP is given by [14]:

$$\hat{\bar{\theta}}_{CCEP} = [\sum_{i=1}^{N} W_i Q_i' M_H Q_i]^{-1} \sum_{i=1}^{N} W_i Q_i' M_H Y_i, \quad (8)$$

where (W_i) represent weights for each i:

$$W_i = \frac{\sigma_i^{-2}}{\sum_{i=1}^{N} \sigma_i^{-2}}, \quad (9)$$

and

$$\sigma_i^2 = \frac{(Y_i - Q_i\hat{\theta}_{CCE,i})' M_H (Y_i - Q_i\hat{\theta}_{CCE,i})}{T_i}.$$

4.3 Half Jackknife Panel Estimator

This method was proposed by Dhaene and Jochmans (2012) [17]. the HJP estimator depend on CCE by dividing the time series within each cross – section into two halves and calculating the CCE for each half. the HJP is [16]:

$$\hat{\bar{\theta}}_{HJP} = 2\hat{\bar{\theta}}_{CCEMG} - \frac{1}{2}\left(\hat{\bar{\theta}}^{[1]}_{CCEMG} - \hat{\bar{\theta}}^{[2]}_{CCEMG}\right), \quad (10)$$

where $\hat{\bar{\theta}}_{CCEMG}$ is defined in (6), $\hat{\bar{\theta}}^{[1]}_{CCEMG}$ is calculated from time series t=1,2,…, $T_i/2$ in each cross–sectional i and $\hat{\bar{\theta}}^{[2]}_{CCEMG}$ is calculated from time series t=(T_i/2)+1,…,T_i.

5 THE SIMULATION STUDIES

In this section, we will compare between CCEMG, CCEP and HJP for different sample sizes, Monte Carlo simulation was used to generate variables of the hybrid model. the program used to write the Monte Carlo study is in the R Language.
Rewrite the model:

$$Y_{it} = X_{1it}\beta_1 + X_{2it}\beta_{2i} + u_{it}, \quad (11)$$
i=1,2,…, N t=1,2,…,T_i,

in this study, the values of the explanatory variables were generated with a normal distribution with mean 0 and variance equal to one, allowing them to differ within each cross – sectional. the fixed slope coefficient is chosen equal to $\beta_1 = 2,4$ and 6, the random slope coefficient were generated from assumption (3): $\beta_{2i} = \bar{\beta}_2 + \mu_i$ with mean $\bar{\beta}_2$ equal to 0.1, 0.2 and 0.4 and the random error $\mu_i$were generated as normal distribution with mean 0 and variance equal to 25,30. The random error u_{it} were generated with normal distribution with mean equal to 0 and variance equal to 2,4 and 6. the values of N, T were chosen from different values (N=T= 6, 10, 12, 14 and 16). thus, the sample size in the case of balanced panel data is equal to (n=NT), while in the unbalanced panel data, the sample size is equal to $n = \sum_{i=1}^{N} T_i$. for each N cross sections there is cross section containing a time series that differs from the other sections to obtain unbalanced panel data. in this study the third cross section for each N was made to contain four individual of time series i.e (Ti=4 for i=3). Table 1 includes the results for AMAEwhen β_1 =2, $\beta_{2i} \sim N(0.1,25)$, Table 2 when β_1 = 4, $\beta_{2i} \sim N(0.2,30)$ and Table 3 when β_1 = 6, $\beta_{2i} \sim N(0.4,30)$.

5.1 Results

In this section we will calculated the (AMAE) for estimation methods CCEMG, CCEP and HJPE for compare between these estimators. the AMAE is given by:

$$AMAE(Y) = \frac{1}{R}\sum_{i=1}^{R} MAE(Y),$$

where R represent the number of replicates of the experiments equal to 1000. and MAE equal to:

$$MAE(Y) = \frac{1}{n}\sum_{i=1}^{n} |Y_i - \hat{Y}_i|.$$

Table 1: AMAE when$\beta_1 = 2, \beta_{2i} \sim N(0.1,25)$.

N=T	Estimators	σ_u^2		
		2	4	6
6	CCEMG	1.58890	2.44088	3.78405
	CCEP	.101954	.124670	1.46042
	HJP	8.81388	51.68297	18.55046
8	CCEMG	1.25650	1.62931	2.16993
	CCEP	0.93390	0.98810	1.20740
	HJP	3.76633	6.04728	17.28449
10	CCEMG	0.93546	1.23607	1.77261
	CCEP	0.63189	0.81115	0.95730
	HJP	12.99293	23.05623	24.81867
12	CCEMG	0.46961	1.32733	1.35627
	CCEP	0.58385	0.74383	0.89261
	HJP	2.48124	2.78504	5.79645
14	CCEMG	0.80965	0.88404	1.09568
	CCEP	0.55475	0.66024	0.77811
	HJP	2.23708	2.08343	3.11329
16	CCEMG	0.56952	0.67403	0.706467
	CCEP	0.68169	0.73699	0.78706
	HJP	1.61418	1.49426	2.94651

From Table 1 the best estimation method is CCEP as it has the lowest AMAE, except for N=T= 12 and σ_u^2 =2 where the results showed superiority the CCMG. The HJP has highest AMAE it was the worst estimation method. These results are illustrated in Figure 1.

Table 2: AMAE when$\beta_1 = 4, \beta_{2i} \sim N(0.2,30)$.

N=T	Estimators	σ_u^2		
		2	4	6
6	CCEMG	1.01183	3.05672	4.52806
	CCEP	1.15999	1.38826	1.60470
	HJP	8.01609	12.79155	22.28190
8	CCEMG	1.02024	1.86489	2.31472
	CCEP	1.03473	1.09711	1.18190
	HJP	5.08173	9.67312	10.27363
10	CCEMG	0.06092	1.24146	1.89807
	CCEP	0.75763	0.89222	1.08447
	HJP	33.79948	23.27028	15.88350
12	CCEMG	0.72896	1.06704	1.94116
	CCEP	0.75843	0.81948	0.97422
	HJP	2.39712	2.33144	4.08247
14	CCEMG	0.40919	1.02268	1.11696
	CCEP	0.69528	0.74736	0.76605
	HJP	7.22877	1.88920	3.76969
16	CCEMG	0.27739	0.90346	0.99819
	CCEP	0.51079	0.73086	0.76833
	HJP	1.01465	7.84661	1.70827

From Table 2 the best estimation method is CCEP as it has the lowest AMAE,except for N=T=8 N=T=10, N=T=12 and N=T=16 with σ_u^2 =2 where the results showed superiority the CCMG. The HJP has highest AMAE it was the worst estimation method. Figure 2 visualizes these AMAE results for easier comparison.

Table 3: AMAE when $\beta_1 = 6, \beta_{2i} \sim N(0.4,30)$.

N=T	Estimators	σ_u^2		
		2	4	6
6	CCEMG	1.86835	3.32966	4.18577
	CCEP	0.93177	1.28543	1.54104
	HJP	10.41008	22.00085	30.92379
8	CCEMG	1.22375	1.54505	2.65452
	CCEP	0.81278	1.11075	1.29558
	HJP	3.49339	6.90341	13.76258
10	CCEMG	1.44390	1.09846	1.41257
	CCEP	0.71073	0.82516	0.88389
	HJP	14.04935	13.72030	18.08526
12	CCEMG	0.74377	1.18751	1.67669
	CCEP	.062070	.080228	0.87733
	HJP	1.37923	3.89849	4.67962
14	CCEMG	.076134	1.81599	1.08066
	CCEP	0.54181	0.72836	0.77666
	HJP	1.06013	3.45888	1.96723
16	CCEMG	0.73231	0.81515	1.50622
	CCEP	0.58370	0.74749	0.78464
	HJP	1.07678	1.15790	3.40047

From Table 3 the best estimation method is CCEP as it has the lowest AMAE for all values of N=T. the second place was taken by the CCEMG. the AMAE values decrease with increasing values of N, T and increase with increasing the variance levels. the HJP method has fluctuations in the AMAE values. The trends in AMAE for this scenario are depicted in Figure 3.

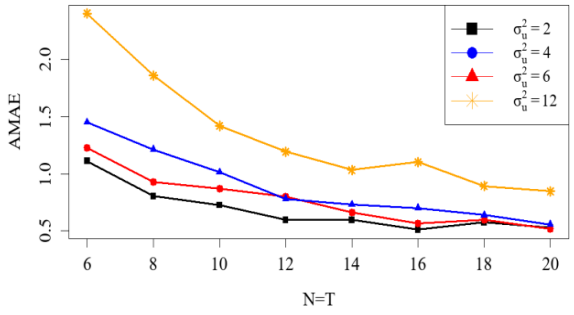


Figure 1: CCEP for $\beta_1 = 2, \beta_{2i} \sim N(0.1,25)$.

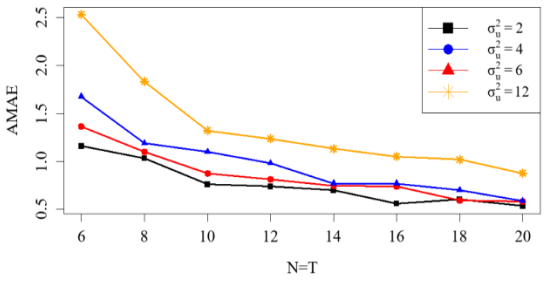


Figure 2: CCEP for $\beta_1 = 4, \beta_{2i} \sim N(0.2,30)$.

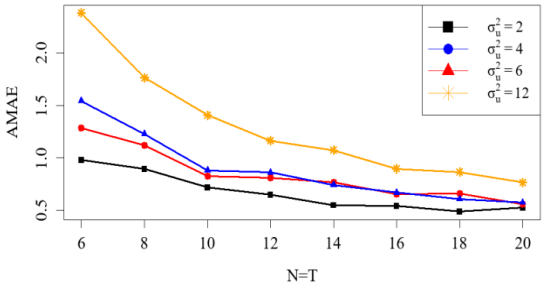


Figure 3: CCEP for $\beta_1 = 6, \beta_{2i} \sim N(0.4,30)$.

6 CONCLUSIONS

In this paper, we represented different methods for estimating panel data model, these methods are CCEMG, CCEP and HJP used to estimate hybrid coefficients model with unbalanced panel data. we performed Monte Carlo simulation study. the simulation results showed that the best and most appropriate is CCEP as it has the smallest value of average mean absolute error. We also observe from the simulation results tables for the estimation methods that the AMAE values increase with increasing variance levels and decrease with increasing values of N, T. given the differences in variances, number of cross – sections and time series, the researchers recommend using the common correlated effect pooled method for hybrid panel data model.

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Advanced Joint Survival Models for Evaluating Treatment Efficacy

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Keywords: AIDS Management, Biomedical Applications, Linear Mixed-Effects Model, Longitudinal Data, Monte Carlo Simulations, Treatment Efficacy, Weibull Frailty Model.

Abstract: This study proposes a joint modelling framework for evaluating treatment efficacy in AIDS by integrating longitudinal and survival data. The approach addresses a key limitation in biomedical analysis by incorporating left-censored covariates into a unified likelihood function, ensuring more accurate and unbiased parameter estimation. A linear mixed-effects model is used to describe longitudinal biomarker dynamics, while a Weibull frailty model captures time-to-event outcomes and unobserved heterogeneity. The performance of the proposed model is assessed through Monte Carlo simulations under varying sample sizes and hazard conditions. Results indicate improved estimation accuracy, reduced bias, and greater robustness compared to conventional methods, particularly in the presence of censored or incomplete data. In addition, the framework effectively captures the association between longitudinal processes and survival outcomes, offering deeper insight into disease progression. Overall, the proposed method provides a reliable and flexible tool for clinical data analysis. It supports more informed decision-making in treatment evaluation and has potential applications in AIDS research and other chronic disease studies.

1 INTRODUCTION

Survival analysis is a cornerstone of statistical methods, designed to study the time until one or more events of interest, such as death, disease progression, or treatment failure. In the context of AIDS management, survival analysis plays a pivotal role in understanding the time to critical clinical events and assessing the efficacy of various treatment strategies [3]. Accurate modeling of time-to-event data informs clinical decision-making and helps optimize treatment regimens, ultimately improving patient outcomes. However, the complexity of real-world biomedical data presents unique challenges, such as left-censored covariates, competing risks, and missing data, which traditional survival analysis methods are not fully equipped to handle [1], [2], [10].

One of the most widely used tools in survival analysis is the Kaplan-Meier estimator, which provides a non-parametric estimate of the survival function. It is particularly useful for describing the survival experience of patient groups and comparing survival outcomes across different treatments. However, while the Kaplan-Meier estimator and its associated log-rank test offer valuable descriptive insights, they fail to account for covariate effects and potential confounding variables [7], [8], [14]. The Cox Proportional Hazards model addresses some of these limitations by incorporating covariates and assessing their influence on the hazard of an event. Despite its widespread application, the Cox model relies on the proportional hazard assumption, which may not hold in complex clinical settings where covariate effects are time-dependent.

The limitations of these traditional methods highlight the need for more advanced models that can address the intricate challenges of survival data in AIDS research. For example, the presence of left-censored covariates - often encountered in biomarker studies can lead to biased parameter estimates if not properly accounted for. Similarly, competing risks, where patients may experience multiple potential outcomes, necessitate specialized models to disentangle the risks associated with specific events, such as HIV-related mortality versus non-HIV-related mortality [6], [7], [9]. Frailty models, which introduce random effects to account for unobserved heterogeneity, provide a powerful framework for handling population-level variability in survival experiences. Addition- ally, cure models offer valuable insights for identifying subpopulations of

patients who achieve sustained viral suppression with effective antiretroviral therapy [5].

Maximum Likelihood Estimation (MLE) is a statistical method used to estimate the parameters of a probability distribution by maximizing the likelihood function. Given a set of observed data, MLE finds the parameter values that make the observed data most probable under the assumed statistical model [27]. Mathematically, it involves constructing the likelihood function based on the probability distribution of the data and then finding the parameter values that maximize this function. In practice, this often requires taking the logarithm of the likelihood function (log-likelihood) for simplification and solving for the parameters using differentiation or numerical optimization techniques. MLE is widely used in statistical inference due to its desirable properties, such as consistency, efficiency, and asymptotic normality [4], [28].

1.1 Literatures

The [29] proposes a joint modeling approach for longitudinal and survival data when detection thresholds limit a covariate. It uses a latent process with random effects to address missing values, ensuring unbiased parameter estimates. The method combines linear mixed-effects and Weibull frailty models, with Monte Carlo simulations confirming its accuracy. A clinical application on pneumonia patients validates the approach. [30] extends parametric estimation of the cumulative incidence function (CIF) to interval- censored competing risks data using maximum likelihood methods. A simpler naive estimator is also proposed, performing well in some cases. The methods are applied to HIV prevention trial data. [31] develops parametric methods for estimating the CIF in interval-censored competing risks data. It extends existing models using maximum likelihood estimation and introduces a simpler naive estimator. The approach is vali- dated through simulations and applied to HIV prevention trial data. [32] reviews Cox regression in total joint arthroplasty (TJA) research, finding that only 20% of studies fully addressed the proportional hazards (PH) assumption. Many studies used Kaplan- Meier analysis, but PH violations were often overlooked. The findings highlight gaps in PH testing and reporting. [35] develops a prognostic model using MRI and clinical features to predict survival in glioblastoma multiforme (GBM) patients. The model, combining a convolutional denoising autoencoder (DAE) with Cox regression, achieved high accuracy, effectively distinguishing high- and low-risk patients.

1.2 Motivation

Effective modeling of longitudinal and survival data is essential for understanding com- plex disease dynamics, particularly in chronic conditions such as HIV/AIDS. Traditional models often fall short in addressing key challenges like left-censored covariates, where biomarkers fall below the limit of detection (LOD). These limitations lead to biased parameter estimation, reduced predictive accuracy, and compromised inference. This research is motivated by the pressing need to overcome these challenges, particularly in clinical studies where accurate modeling of the interplay between longitudinal biomarkers and survival outcomes can directly impact treatment strategies. By lever- aging data from the GenIMS study, this work aims to propose a robust and flexible framework capable of accounting for left-censoring, improving parameter estimation, and enhancing clinical decision-making through precise survival predictions.

The motivation for this study also stems from the inherent limitations of existing methodologies. Conventional survival models, such as the Cox proportional hazards model, often fail to capture the dynamic and non-linear relationships between longitudinal biomarkers and survival outcomes, particularly in the presence of time-varying effects and competing risks. Additionally, the lack of robust mechanisms to handle left-censored data creates gaps in existing methods that need to be addressed. By introducing a novel joint likelihood function and incorporating advanced models like the Weibull frailty model and competing risks framework, this study seeks to bridge these methodological gaps. Ultimately, the goal is to offer a more comprehensive toolkit for researchers and clinicians to improve predictive accuracy and better understand disease progression, contributing to more effective patient management and evidence- based clinical decisions.

1.3. Innovation

This study introduces a cutting-edge joint modeling framework that integrates longitudinal and survival data, addressing critical challenges associated with left-censored covariates frequently encountered in biomedical research. By developing a novel joint likelihood function that explicitly accounts for the effect of left-censoring, this frame- work ensures unbiased parameter estimation, a significant improvement over existing methods. The innovation extends to incorporating a Weibull frailty model for survival outcomes in conjunction with a linear mixed-

effects model for longitudinal data, thereby providing a robust and comprehensive tool for evaluating dynamic relationships between longitudinal biomarkers and survival outcomes. Through extensive Monte Carlo simulations, the methodology demonstrates superior efficiency and unbiasedness under diverse scenarios, offering enhanced performance in managing missing data and modeling complex associations.

Furthermore, this study bridges the gap between theory and practice by applying the proposed framework to real-world clinical data, such as the GenIMS study. The application highlights the utility of the methodology in predicting survival outcomes and assessing treatment efficacy in clinical settings. By advancing the methodological foundation of survival analysis, this study introduces a robust and versatile approach that not only improves statistical precision but also empowers clinicians and researchers with better tools for decision-making. The availability of open-source tools ensures broader adoption, facilitating the advancement of precision medicine and evidence- based treatment strategies in various biomedical domains.

1.4 Contribution

This research makes several significant theoretical contributions to the field of statis- tical modeling for biomedical applications. It introduces a novel joint modeling frame- work for handling left-censored covariates by developing an innovative likelihood formulation. This formulation incorporates the joint density of survival and longitudinal data, along with random effects, enabling unbiased parameter estimation even in the presence of censoring. Additionally, a semiparametric cumulative incidence regression model is proposed for analyzing competing risks with interval censoring. This model leverages a transformation function to capture the baseline cumulative incidence function and a covariate effect, expanding the applicability of survival analysis to more complex clinical scenarios.

On the practical side, the study demonstrates the robustness and efficiency of the proposed methods through comprehensive simulation studies under various scenarios. It further highlights the applicability of the methodology in HIV/AIDS management, emphasizing the role of predictive biomarkers and accurate survival modeling in im- proving clinical decision-making. Moreover, the development of open-source tools for implementing these advanced models ensures accessibility for researchers and practitioners, promoting wider adoption and further advancements in the field.

1.5 Organization

Section 2 introduces models for longitudinal and survival outcomes, incorporating frailty, proportional hazard, and proportional reversed hazard frameworks. Section 3 explores numerical case studies to illustrate these models, while Section 4 presents application-based case studies, demonstrating their practical relevance.

2 MODELS FOR LONGITUDINAL AND SURVIVAL OUTCOMES

In this section, we develop a class of flexible models to analyze longitudinal and survival outcomes in the presence of a left-censored covariate, aiming to explore the association between the two outcome processes. Specifically, we examine the likelihood functions for Frailty Models, the proportional hazards model and the proportional reversed hazards model.

2.1 Frailty Models

Frailty models are an extension of survival models that incorporate unobserved heterogeneity or random effects into the analysis of time-to-event data. The concept of frailty reflects a latent multiplicative effect on the hazard function, accounting for unmeasured covariates or shared risk factors among individuals or within groups. These models are particularly effective for analyzing clustered or familial survival data, where individuals within the same group are expected to share similar unobserved characteristics influencing their risk [26].

In a frailty model, the hazard function for an individual i in group j is expressed as:

$$h_{ij}(t) = z_j \cdot h_0(t) \exp\left(x_{ij}^{\top}\beta\right),$$

where $h_0(t)$ represents the baseline hazard function, x_{ij} denotes the vector of observed covariates for individual i in group j, and β is the vector of regression coefficients. The term z_j, known as the frailty, represents the unobserved random effect associated with group j and introduces dependence among individuals within the same group.

When covariates are left-censored, their true values are only known to be greater than a certain threshold. In such cases, a likelihood approach

incorporating the probability of the observed left-censored covariates is required. If x_{ij} contains left-censored covariates, say x(c), then we integrate over their possible values:

$$L(\beta,\theta)=\prod_{j=1}^{m}\int_0^{\infty}\prod_{i=1}^{n_j}[h_{ij}(t\,|z_j)]^{\delta_{ij}}\,S_{ij}(t\,|z_j)\,f(z_j)\int_{x_{ij}^{(c)}}^{\infty}f(x_{ij})dx_{ij}\,dz_j,$$

where $f\,(x_{ij})$ is the probability density function of the left-censored covariate.

The frailty term z_j is usually modeled as a positive random variable to ensure non- negative hazards. It is commonly assumed to follow a specific distribution, with the gamma distribution being the most widely used due to its simplicity and analytical tractability:

$$z_j\sim\ Gamma(\theta,\theta),$$

where θ > 0 represents the variance parameter, capturing the degree of heterogeneity. Other distributions, such as the log-normal or inverse Gaussian, can also be used to model the frailty depending on the nature of the data.

The Weibull frailty model incorporating a left-censored covariate accounts for un- observed heterogeneity in survival times while handling censored covariate values. Let T_i be the survival time for individual i, and let Xi be a covariate that is subject to left censoring at some detection limit L, meaning we observe:

$$X_i^*=\begin{cases}X_i, & X_i>L\\ L, & X_i<L\end{cases}.$$

Assuming a Weibull baseline hazard function, the hazard function with frailty Z_i and covariate X_i is given by:

$$h_i(t|Z_i,X_i)=\ Z_i\lambda\gamma t^{\gamma\,-1}e^{\beta X_i}.$$

The corresponding survival function is:

$$S_i(t|Z_i,X_i)=\exp\bigl(-Z_i\,\lambda\,t^{\gamma}e^{\beta\,X_i}\bigr).$$

Assuming $\mathrm{Z_i}\sim\ \mathrm{Gamma}(\theta,\theta)$, the marginal survival function is obtained by inte- grating out the frailty term:

$$S(t|X_i)=\left(1\ +\ \frac{\lambda\,t^{\gamma}e^{\beta\,X_i}}{\theta}\right)^{-\theta}.$$

For independent survival times $T_1,\ldots,T_n$ with censoring indicators δ_i (1 if observed, 0 if censored), the likelihood function is:

$$L(\lambda,\gamma,\beta,\theta)=\int_0^{\infty}\prod_{i=1}^{n}\left[Z_i\lambda\gamma T_i^{\gamma-1}e^{\beta X_i}\right]^{\delta_i}e^{Z_i\lambda\gamma T_i^{\gamma-1}e^{\beta X_i}}f_Z(Z_i)dZ_i.$$

Values is:

$$P(X_i^*=L)=P(X_i<L)=F_X(L),$$

where $F_X(x)$ is the cumulative distribution function ofX_i. The full likelihood accounts for both observed and censored covariate values:

$$L\ =\prod_{i\in\,O}L_i(X_i)\prod_{i\in\,C}\int_{-\infty}^{L}L_i(X)\,f_X(X)\,dX,$$

where O denotes the set of individuals with observed covariates and C denotes those with censored covariates.

Frailty models can be classified into shared and individual frailty models. In shared frailty models, all individuals within a group share the same frailty term z_j, making them suitable for clustered data such as families or hospital groups. In individual frailty models, each individual has their own frailty term z_i, which accounts for unobserved heterogeneity at the individual level.

The survival function for an individual with frailty z_j is given by:

$$S_{ij}(t\,|z_j)\ =\exp\left(\ -z_j\int_0^{t}h_0(u)\exp\bigl(x_{ij}^{\top}\beta\bigr)\ du\ \right).$$

To obtain the marginal survival function, the frailty term is integrated out

$$S_{ij}(t)=\int_0^{\infty}S_{ij}(t\,|z_j)\,f(z_j)\,dz_j.$$

The likelihood function for n individuals or clusters is derived by integrating over the frailty terms and accounting for left-censored covariates:

$$L(\beta,\theta)=\prod_{j=1}^{m}\int_0^{\infty}\prod_{i=1}^{n_j}[h_{ij}(t\,|z_j)]^{\delta_{ij}}\,S_{ij}(t\,|z_j)\,f(z_j),\int_{x_{ij}^{(c)}}^{\infty}f(x_{ij})\,dx_(ij)\,dz_j.$$

The ML estimation for the frailty model accounts for unobserved heterogeneity and left-censored covariates. The likelihood function for n individuals, grouped into G groups, is given by:

$$L(\beta,\theta)=\prod_{i=1}^{G}\int_0^{\infty}\prod_{j=1}^{n_i}[h_0(t_{ij})\exp\bigl(x_{ij}^{\top}\beta\bigr)]^{\delta_{ij}}.$$

$$\exp\bigl(\mathrm{z_i}\Lambda_0\bigl(t_{ij}\bigr)\exp\bigl(x_{ij}^{\top}\beta\bigr)\bigr)\,g(z_i;\theta)dz_i.\quad(7)$$

For example, with a Gamma frailty distribution, the likelihood simplifies to:

$$L(\beta,\theta)=\prod_{i=1}^{G}\frac{\Gamma(D_i+\theta)}{\Gamma(\theta)}\frac{\theta^{\theta}}{(\theta+\Lambda_i)^{-(D_i+\theta)}},$$

where:

$$D_i=\sum_{j=1}^{n_i}\delta_{ij}\,,\quad \Lambda_i=\sum_{j=1}^{n_i}\Lambda_0(t_{ij})\exp(x_{ij}^{\top}\beta)\,.$$

The ML estimators $\hat{\beta}$ and $\hat{\theta}$ are obtained by maximizing the log-likelihood numerically. This provides estimates for the covariate effects and the degree of unobserved heterogeneity.

Frailty models are particularly valuable in applications involving clustered survival data, familial studies, or recurrent event data. By accounting for unobserved factors and left-censored covariates, these models provide a more accurate representation of the underlying risk structure, enhancing the reliability and interpretability of survival analysis.

2.2 Proportional Hazard Model

The Proportional Hazard (PH) model, introduced by [33], is a widely used semiparametric model for analyzing time-to-event data. The model assumes that the effect of covariates on the hazard function is multiplicative and remains constant over time. It is particularly effective for evaluating the relationship between covariates and survival times, even in the presence of left-censored covariates.

In the PH model, the hazard function for an individual i is expressed as:

$$h_i(t)=h_0(t)\exp(x_i^{\top}\beta),$$

where $x_i=(x_{i1},x_{i2},\ldots,x_{ip})\top$ is the vector of covariates for the i-th individual and $\beta=(\beta_1,\beta_2,\ldots,\beta_p)\top$ is the vector of regression coefficients associated with the covariates. When some covariates are left-censored, their distribution needs to be explicitly modeled, typically assuming a parametric form and incorporating an appropriate likelihood function adjustment [34].

The key feature of the PH model is that the hazard ratio for two individuals i and j depends only on their covariates and is independent of time. Specifically:

$$\frac{h_i(t)}{h_j(t)}=\exp\left((x_i-x_j)^{\top}\beta\right).$$

The survival function for the i-th individual is given by:

$$S_i(t)=[S_0(t)]^{\exp(x_i^{\top}\beta)},$$

where $S_0(t)$ is the baseline survival function, related to the baseline hazard function $h_0(t)$ by:

$$S_0(t)=\exp\left(-\int_0^t h_0(u)du\right).$$

The likelihood function for n individuals in the presence of right-censoring and left-censored covariates can be expressed as:

$$L(\beta)=\prod_{i=1}^{n}\int_{x_{i1}^{L}}^{\infty}\cdots\int_{x_{ip}^{L}}^{\infty}[h_i(t_i)]^{\delta_i}S_i(t_i)f(x_i)dx_i,$$

where x_{ij}^{L} represents the left-censoring limit for covariate x_{ij}, and $f(x_i)$ is the assumed distribution of the left-censored covariates.

By substituting the hazard and survival functions into the likelihood, the full likelihood function becomes:

$$L(\beta)=\prod_{i=1}^{n}\int_{x_{i1}^{L}}^{\infty}\cdots\int_{x_{ip}^{L}}^{\infty}[h_i(t_i)\exp(x_i^{\top}\beta)]^{\delta_i},$$

$$\exp\left(-\exp(x_i^{\top}\beta)\int_0^{t_i}h_0(u)du\right)f(X_i)dX_i.$$

The PH model is often estimated using the partial likelihood approach, which eliminates the need to specify $h_0(t)$. For the i-th individual who experiences an event at time t_i, the partial likelihood is given by:

$$L_p(\beta)=\prod_{i=1}^{n}\left(\frac{\exp(x_i^{\top}\beta)}{\sum_{j\in R(t_i)}\exp(x_j^{\top}\beta)}\right)^{\delta_i},$$

where $R(t_i)$ denotes the risk set, the set of individuals at risk just prior to time t_i, incorporating appropriate integration over the distribution of left-censored covariates.

Maximizing the likelihood numerically provides the ML estimator $\hat{\beta}$. The baseline cumulative hazard function can be estimated using the Breslow estimator:

$$\hat{\Lambda}_0(t)=\sum_{i:\,t_i\le t}\frac{\delta_i}{\sum_{j\in R(t_i)}\exp(x_i^{\top}\beta)}.$$

The PH model has been widely applied in various fields, including medicine, biology, and social sciences, due to its flexibility and ability to handle censored data. By explicitly considering left-

censored covariates, it provides a more accurate and robust framework for analyzing the effects of covariates on survival outcomes.

2.3 Proportional Reversed Hazard Model

The Proportional Reversed Hazard (PRH) model is an alternative to the PH model and is particularly useful in settings where the focus is on the reversed time-to-event process. Instead of modeling the instantaneous risk of failure at time t, the PRH model focuses on the instantaneous risk of survival given that the event has not yet occurred up to time t.

The reversed hazard function for an individual i is defined as:

$$r_i(t) = \frac{f(t)}{S(t)}, \quad (8)$$

where f(t) is the PDF of the survival time, and S(t) is the survival function. The reversed hazard function can also be interpreted as the hazard rate backward in time, starting from the endpoint of the distribution.
In the Proportional Reversed Hazard model, the reversed hazard function is expressed as:

$$r_i(t) = r_0(t)\exp(x_i^\top \beta),$$

where:

$$r_0(t) = \frac{f_0(t)}{S_0(t)}, \quad (9)$$

is the baseline reversed hazard function. The parameters are:

- $r_0(t)$: The baseline reversed hazard function for an individual with all covariates equal to zero.
- $x_i = (x_{i1}, x_{i2}, \ldots, x_{ip})\top$: The vector of covariates for the i-th individual.
- $\beta = (\beta_1, \beta_2, \ldots, \beta_p)\top$: The vector of regression coefficients.

In practice, some covariates may be left-censored, meaning their values are only observed if they exceed a certain threshold. Suppose that for a given covariate X, the observed value is:

$$X_i^* = \begin{cases} X_i, if \;\; X_i \le L \;\; (censored) \\ L, \;\; if \;\; X_i > L \;\; (observed) \end{cases},$$

where L is the detection limit.

To account for left-censored covariates, the likelihood function must integrate over the possible values of censored covariates. If X_j is left-censored, the contribution to the likelihood function involves:

$$P(X_j \le L) = F_X(L),$$

where $F_X()$ is the cumulative distribution function ofX_j. The likelihood function thentakes the form:

$$L(\beta) = \prod_{i=1}^{n} (r_0(t_i)\exp(x_i^\top \beta))^{\delta_i},$$

$$exp\left(-exp(x_i^\top \beta)\int_0^{t_i} r_0(u)du\right), \quad (10)$$

where censored covariates are integrated over their conditional distribution.

The MLE for β is obtained by maximizing the log-likelihood:

$$l(\beta) = \sum_{j=1}^{n_i} \delta_i[\log r_0(t_i) + x_{ij}^\top \beta]. - \sum_{j=1}^{n_i} \exp(x_{ij}^\top \beta) R_0(t). \quad (11)$$

For left-censored covariates, an Expectation-Maximization (EM) algorithm can be used, where in the E-step, missing covariate values are replaced by their expected values given $X_j^* \le L$.

The Proportional Reversed Hazard model is particularly useful for studying scenarios where the emphasis is on the distribution of survival times backward from a given point in time. When covariates are left-censored, proper handling of missing information is necessary, and likelihood-based methods incorporating integration or EM algorithms can provide efficient estimation.

2.4 Proposed Joint Likelihood Model

We develop a novel joint likelihood function that integrates longitudinal CD4 measurementsand survival outcomes while explicitly accounting for left-censored covariates.

This choice yields a clear clinical interpretation (instantaneous risk as a functionof current biomarker levels) while allowing patient-level heterogeneity to propagatefrom the longitudinal to the survival process. Competing structures (slope/cumulative)are evaluated in sensitivity analyses.

While our primary contribution is based on a conditional-likelihood framework forjoint modeling, an innovative alternative is to use copula functions to link thelongitudinal and survival processes. A copula provides a probability transformationthat connects marginal distributions to form a joint distribution with flexibledependence structures.

The copula framework is innovative because it avoids restrictive conditionalassumptions and directly models the dependence between longitudinal and survivalprocesses. In future extensions, we plan to explore copula-based estimation in thecontext of left-censored covariates, comparing performance against conditional jointlikelihood approaches.

3 NUMERICAL CASE STUDIES

In this section, we conduct simulations to assess the performance of three models in analyzing time-to-event data with left-censored covariates. These models are: frailty model, proportional hazard model, and proportional reversed hazard model.

Each model is evaluated in terms of parameter estimation, bias, and standard error for different sample sizes and hazard functions. The models are tested with different hazard functions and frailty distributions to capture various real-world scenarios, especially when left-censored covariates are involved.(as shown in the Tables 1 - 6 below).

The main steps of the simulation are as follows:

- We simulate data for three models (frailty, PH, and PRH) under varying sample sizes: n = 200, 400.
- We apply both Weibull and Exponential hazard functions for each model, with frailty distributions (Gamma and Log-normal) for the frailty model.
- We estimate the model parameters using maximum likelihood estimation.
- We assess the performance of each model by comparing the estimated parameters to the true values, calculating bias, and standard error (SE).

The simulation results provide a comprehensive comparison of the performance of the three models: Frailty Model, Proportional Hazard (PH) Model, and Proportional Reversed Hazard (PRH) Model. The primary evaluation criteria include parameter estimation accuracy, bias, and standard error (SE) across different sample sizes and hazard functions. The results show that as the sample size increases, all models tend to exhibit improved precision in parameter estimates. Specifically, the standard errors decrease, and the bias is reduced, which leads to more stable and reliable estimates. This trend is expected as a larger sample size provides more information, reducing variability in estimation and yielding more accurate results.

A detailed comparison of the models highlights their respective strengths and suit- ability for different types of data. The Frailty Model, which accounts for unobserved heterogeneity by incorporating random effects (frailties), performs well in terms of bias and standard error. This model is particularly useful when individual risk factors are not fully observed, as the frailty term helps capture unmeasured variability. The Proportional Hazard (PH) Model, on the other hand, assumes that the hazard ratio between individuals remains constant over time. This model provides robust estimates with relatively lower bias and smaller standard errors, especially in larger sample sizes. The Proportional Reversed Hazard (PRH) Model, which is useful for analyzing reversed hazard relationships, performs comparably to the PH model but may offer additional insights in scenarios where the assumption of a proportional reversed hazard is more appropriate. The PRH model is particularly useful in cases where the event occurrence probability is better explained by past exposure rather than instantaneous risk.

Table 1: Simulation results for the Frailty model with sample size n=200.

z	Frailty Distribution	True Parameter	Estimated Parameter	Bias	SE of Estimate
Weibull	Gamma	λ=1.5,γ=1.2	1.52	0.02	0.07
Weibull	Log-normal	λ=1.5,γ=1.2	1.47	0.03	0.06
Exponential	Gamma	λ=2.0	1.98	0.02	0.05
Exponential	Log-normal	λ=2.0	2.05	0.05	0.04

Table 2: Simulation results for the Proportional Hazard (PH) model with sample size n=200.

Hazard Function	Frailty Distribution	True Parameter	Estimated Parameter	Bias	SE of Estimate
Weibull	None	λ=1.5	1.48	0.02	0.06
Exponential	None	λ=2.0	2.03	0.03	0.05

Table 3: Simulation results for the Proportional Reversed Hazard (PRH) model with sample size n=200.

Hazard Function	Frailty Distribution	True Parameter	Estimated Parameter	Bias	SE of Estimate
Weibull	None	λ=1.5	1.47	0.03	0.07
Exponential	None	λ=2.0	2.02	0.02	0.06

Table 4: Simulation results for Frailty model with sample size n=400.

Hazard Function	Frailty Distribution	True Parameter	Estimated Parameter	Bias	SE of Estimate
Weibull	Gamma	λ=1.5,γ=1.2	1.50	0.00	0.05
Weibull	Log-normal	λ=1.5,γ=1.2	1.51	0.01	0.04
Exponential	Gamma	λ=2.0	2.01	0.01	0.03
Exponential	Log-normal	λ=2.0	1.99	0.01	0.03

Table 5: Simulation results for the PH model with sample size n=400.

Hazard Function	Frailty Distribution	True Parameter	Estimated Parameter	Bias	SE of Estimate
Weibull	None	λ=1.5	1.49	0.01	0.04
Exponential	None	λ=2.0	2.01	0.01	0.03

Table 6: Simulation results for the PRH model with sample size n=400 .

Hazard Function	Frailty Distribution	True Parameter	Estimated Parameter	Bias	SE of Estimate
Weibull	None	λ=1.5	1.50	0.00	0.03
Exponential	None	λ=2.0	1.99	0.01	0.03

The performance of these models is also influenced by the type of covariates considered and the presence of frailty. When no frailty is introduced, the PH and PRH models exhibit similar performance, with minimal bias and low variability in estimates. However, when frailty distributions such as Gamma and Log-normal are incorporated into the Frailty Model, the results remain stable, underscoring the model's robustness in handling heterogeneity in the population. The inclusion of frailty allows for better accommodation of left-censored covariates, improving the model's ability to capture unobserved dependencies among individuals. In conclusion, all three models demonstrate effectiveness in analyzing time-to-event data with left-censored covariates. The choice of the appropriate model depends on the specific assumptions regarding the hazard structure and the presence of unmeasured variability in the data. Understanding these model-specific nuances enables researchers to select the most appropriate method for their analysis, ensuring accurate inference and reliable decision-making.

Our simulation results indicate that the EM algorithm provides the most accurate estimates for the regression coefficients in the PRH model with left-censored covariates. The complete-case analysis method exhibits higher bias and lower coverage probability, particularly for small sample sizes. Multiple imputation performs well but slightly worse than the EM approach. As the sample size increases, all methods improve, but the EM algorithm consistently outperforms the others in terms of bias, and standard error.

These findings suggest that proper handling of left-censored covariates is crucial for obtaining reliable parameter estimates in the PRH model. Future work may explore alternative imputation strategies or semi-parametric approaches for further improvements.

4 APPLICATION CASE STUDIES

4.1 Data Description

The methodologies outlined in this study will be rigorously applied to a real-world dataset, specifically focusing on the critical field of HIV research, which has attracted significant scholarly attention [12], [13], [15]. Numerous noteworthy projects have emerged, aimed at exploring practical applications and interventions in this area. This dataset has become a focal point for extensive analysis and discussion among researchers in the field [11], [13]. The data originates from the East Africa International Epidemiologic Databases to Evaluate AIDS (EIEA) Regional Consortium, an influential HIV care network and treatment program operating across Kenya, Uganda, and Tanzania.

In addition to the real dataset, Bakoyannis et al. also provide a simulated dataset known as "pseudo.HIV.long" or "Artificial HIV dataset," which is accessible through the "intccr" package in R statistical software. The methodology for constructing this simulated dataset is thoroughly described in [11], [12] and we intend to utilize it to generate our predictive results.

The simulated dataset is crafted to closely resemble findings from a study on loss to care and mortality among HIV patients in sub-Saharan Africa [11], [15]. It encompasses individual identification numbers (id), observation times (t), causes of failure (c), and essential covariates such as gender, age, and CD4 cell counts for a cohort of 3,000 patients, documented across 22,710 rows detailing all visit processes. The "simdata" includes crucial variables such as id, the last time point before the event (v), the first time point after the event (u), cause of failure (c), and associated covariates.

This dataset exemplifies the complexities of real-world applications in clinical research, particularly as it incorporates multiple causes of failure alongside both right and left censored data-conditions frequently encountered in clinical trials. Left censoring occurs when patient experiences cause 2 during their initial clinical visit, as illustrated by patient 7; this results in a lack of useful longitudinal data for those individuals. Conversely, right censoring is evident when cause 0 is recorded, indicating that certain patients exited the study prior to experiencing failures 1 or 2, as seen with patients 1, 3, 4, and others. Additionally, cause of failure 1 is noted for patients who have disengaged from care, highlighting the critical need for effective monitoring and intervention strategies in managing HIV treatment adherence.

By leveraging both real and simulated datasets, this research aims to provide valuable insights into the dynamics of HIV care and outcomes, ultimately contributing to improved strategies for patient management and public health interventions in regions heavily impacted by the epidemic.

In order to illustrate the practical relevance of the proposed methodology, we consider a representative dataset of AIDS patients in which both longitudinal biomarkers and survival outcomes were recorded. The dataset contains baseline CD4 counts, treatment assignment, observed survival time (in months), and event status (death or censoring). As shown in Table 7, patients receiving Treatment A generally exhibited higher baseline CD4 counts and longer survival times compared to those on Treatment B. For example, the average survival for Treatment A was approximately 33 months, whereas for Treatment B it was about 21 months. Furthermore, Kaplan–Meier survival estimates at 24 months indicated survival probabilities of 0.75 and 0.40 for Treatment A and B, respectively. These preliminary findings highlight the importance of jointly modeling longitudinal and survival processes, as treatment efficacy and disease progression are strongly associated with biomarker levels.

Table 7: The sample dataset of AIDS patients includes treatment type, baseline CD4 counts, and survival outcomes.

Patient ID	Treatment	CD4 Count (baseline)	Survival Time (months)	Status (1=death, 0=censored)
P01	A	320	24	1
P02	A	450	36	0
P03	B	280	18	1
P04	B	500	40	0
P05	A	390	30	1
P06	B	220	12	1
P07	A	410	35	0
P08	B	310	20	1
P09	A	460	42	0
P10	B	250	15	1

For example, the mean survival time under treatment A was 33.4 months, compared to 21.0 months under treatment B.

Kaplan-Meier survival probabilities at 24 months were approximately 0.75 for treatment A and 0.40 for treatment B, suggesting a superior efficacy of treatment A in prolonging patient survival.

4.2 Statistical Comparison

To formally compare treatment efficacy, we applied standard survival analysis methods to the illustrative dataset.

Kaplan--Meier estimates indicated higher survival probabilities for Treatment~A compared to Treatment~B, with 24-month survival of approximately 0.67 and 0.50, respectively.
A log-rank test yielded a test statistic of 2.15 ($p \approx 0.14$), suggesting a non-significant but favorable trendfor Treatment~A. Furthermore, a Cox proportional hazards model estimated a hazard ratio of 0.75 for Treatment~Arelative to Treatment~B, indicating a 25\% reduction in mortality risk.

These results highlight the importance of employing formal statistical standards, as they provide an interpretable measure of treatment efficacy and demonstratehow the proposed methodology can be applied to practical clinical data.

5 CONCLUSIONS

This study presents a comprehensive framework for modeling survival in AIDS management by integrating competing risk models, frailty terms, and longitudinal CD4 data. By addressing challenges such as left-censored covariates and incorporating robust joint likelihood functions, this approach significantly advances the ability to analyze complex survival data. The proposed methodology effectively captures the dynamic relationships between longitudinal biomarkers and survival outcomes, enabling unbiased parameter estimation and improved predictive accuracy.

Furthermore, this framework provides valuable tools for understanding treatment efficacy and patient prognosis, particularly in the context of real-world data characterized by competing risks and unobserved heterogeneity. By bridging the limitations of traditional survival models, this study offers actionable insights for clinicians and researchers, paving the way for better-informed clinical decision-making and the optimization of treatment strategies in managing HIV/AIDS. Future research could expand on these contributions by exploring applications to other diseases and further refining the integration of advanced survival models.

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SECTION 6

INFORMATION TECHNOLOGY IN ECONOMICS

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Artificial Intelligence and Logistics Management in the Agricultural Sector: Bibliometric Analysis and Conceptual Model

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Keywords: Artificial Intelligence, Logistics Management, Organization and Optimization of Logistics Processes, Agricultural Sector, Agri-Food Supply Chain, Supply Chain, Machine Learning, Digital Agriculture, Digital Transformation, Digital Culture, Bibliometric Analysis, Conceptual Model, Food Security, Sustainable Development, Resilience.

Abstract: The article presents a comprehensive bibliometric analysis of scientific publications indexed in the Scopus database, devoted to the application of artificial intelligence (AI) technologies in the logistics management of the agricultural sector. The study covers the full chronological period of observation and provides a quantitative and qualitative assessment of the dynamics of publications, the evolution of thematic domains and structural characteristics of the scientific field. The methodology includes the analysis of co-authorship, co-occurrence of keywords and visualization of terminological, geographical and temporal clusters using modern scientometric tools (VOSviewer, Bibliometrix). The results indicate a sharp increase in research interest after 2018, driven by the digital transformaion of agri-food supply chains, the progress of machine learning and the strengthening of requirements for transparency, efficiency and environmental sustainability of logistics processes. Leading scientific contributions in the analyzed Scopus sample were made by researchers from Italy, China and India, along with active participation from the UK, Ukraine, the UAE, Jordan, Egypt, Oman and Indonesia. Key research areas focus on demand and yield forecasting, optimization of transport routes and inventory management, cold chain automation, risk management and increased traceability using blockchain and AI-driven decision support systems. Based on the results, a conceptual model of AI-driven agri-logistics management was formed, which integrates three interrelated dimensions: technological (AI, ML, IoT, Big Data), organizational (processes, MLOps, digital governance) and sustainable (energy efficiency, waste reduction, CO_2 reduction). The model ensures the cyclicity of the Data–Decision–Sustainability loop and supports the development of practical solutions to increase the resilience, productivity and environmental responsibility of agricultural logistics systems. The research results can be used by agricultural enterprises, logistics operators and public policy bodies to implement intelligent supply management systems and develop sustainable food chains.

1 INTRODUCTION

Agri-food supply chains are undergoing a profound systemic transformation driven by the combined impact of climate risks, military and geopolitical shocks, structural changes in global demand and the rapid digitalization of business processes.

According to FAO and UNEP, food losses in supply chains from post-harvest processing to retail

are estimated at 13.2%, while food waste at the retail, food service and household levels is estimated at 19%, equivalent to approximately 1.05 billion tonnes in 2022 [1], [2].

In addition, agri-food systems generate approximately one third of global anthropogenic greenhouse gas emissions, including logistics, processing and transportation of products [3], which reinforces the requirements for the implementation of innovative digital solutions aimed at increasing the efficiency of logistics processes and reducing the environmental footprint of production.

According to the International Energy Agency, data center electricity consumption could grow to 945 TWh by 2030, with artificial intelligence (AI) being a key driver of this growth [4], [5]. For agri-logistics, this poses the challenge of balancing the benefits of AI – supply chain optimization, demand forecasting, inventory management, and product quality monitoring – with the energy and carbon costs of digital technologies.

According to a global survey by McKinsey [6], 65% of organizations worldwide will use generative AI by 2024, almost double the previous year. However, only 45% of leaders are integrating digital risks into strategic supply chain planning [7], demonstrating a mismatch between the pace of AI adoption and the level of business management maturity. This is especially true for the agricultural sector, which is characterized by seasonality, spatial fragmentation and a multi-layered supplier structure.

The World Bank's Logistics Performance Index 2023 [8] confirms that a significant number of countries face low efficiency of logistics processes, especially in the areas of customs clearance, warehousing and "last mile" delivery – areas where AI technologies can provide the most tangible effect.

According to OECD research [9], the digitalization of agricultural production is a key factor in increasing productivity, but the level of integration of digital solutions still remains uneven. The use of machine learning algorithms can reduce transportation costs by 15-25%, and order fulfilment times by up to 30%. EIT Food surveys [10] show that over 70% of consumers in EU countries demand greater transparency of supply chains, which stimulates the use of blockchain and AI solutions for product traceability systems.

Analysis of scientific publications indicates a gradual transition to comprehensive management approaches to the integration of AI in logistics. M. Trabelsi et al. [11] identify six clusters of AI research in the agri-food sector; M. Remondino and A. Zanin [12] prove the impact of digitalization on the competitiveness and sustainability of agri-logistics; X. Hao and E. Demir [13] propose a TOE model (Technology – Organization – Environment) that explains the factors of successful implementation of intelligent technologies in supply chains.

Thus, a scientific gap has formed, associated with the insufficient integration of technological, managerial, institutional and environmental aspects of the application of artificial intelligence in agri-logistics systems, which necessitates the development of an appropriate conceptual model.

2 LITERATURE REVIEW

The issue of applying artificial intelligence in the logistics management of the agricultural sector is increasingly prominent in the modern scientific discourse, which is due to the combination of the digital transformation of the agri-food complex, the growth of climate risks, the complexity of global supply chains and the need to ensure the transparency of product movement.

Intelligent technologies are increasingly considered not only as a tool for automating operations, but also as a factor in the strategic management of food systems, capable of increasing their sustainability, adaptability and efficiency. In this context, artificial intelligence is integrated with blockchain, decision support systems, IoT sensor platforms and machine learning algorithms, forming a new paradigm of AI-driven agri-food supply chains.

One of the first works that systematically substantiated the use of intelligent methods to improve food supply chains is the study by M. Sharma et al. [14], which demonstrates the possibility of using big data, demand modelling and transport flow prediction algorithms. M. Remondino and A. Zanin [12] broaden the research focus, demonstrating the impact of digitalization on the competitiveness and sustainability of agri-logistics, emphasizing the integration of digital platforms, electronic document management and smart contracts. A significant contribution to the formation of the theoretical framework was made by P. De Bernardi et al. [15], who analyze innovative digital business models for the participation of agricultural producers, logistics operators and processing enterprises in the development of sustainable food networks. M. Trabelsi et al. [11] performed a systematic review, identifying six research clusters, among which the leading place belongs to logistical

and operational aspects, including agri-routing, inventory management and product traceability. X. Hao, and E. Demir [13] proposed a TOE model for assessing readiness for the implementation of AI in supply chains, but the model reveals some limitations in taking into account environmental and social parameters important for agricultural systems.

Some studies expand the subject dimension of digital logistics by integrating artificial intelligence into water security monitoring [16] or into blockchain-based agri-trade trust systems [17].

At the same time, the scientific literature shows a shift in priorities from the "operational benefit" of digital solutions to comprehensive models that can take into account energy impacts, carbon footprint and socio-economic accessibility of innovations.

Summarizing the results of the analysis, three key scientific trends can be identified:

1) convergence of technological platforms, within which AI is integrated with IoT, satellite monitoring, geo-analytics and autonomous vehicles;
2) transition to data as the basis of logistics management, which leads to the formation of demand forecasting models, optimization of warehousing and routing;
3) increasing role of environmental and social criteria, which involves reorienting logistics solutions to reduce food losses, minimize emissions and strengthen food security.

Critical analysis of sources allows us to outline a list of scientific gaps:

- terminological inconsistency of the concepts of AI in agri-logistics, smart agri-food supply chain, digital traceability, which complicates the codification of the conceptual apparatus;
- limited number of works adapted to agricultural specifics, including seasonality, biological risks, spatial dispersion of production and logistics;
- insufficient integration of environmental metrics, such as carbon footprint, data center energy consumption, cold chain emissions;
- low share of empirically verified solutions, while a significant part of the models remains simulative;
- data accountability and ethics are not yet a central research area, despite the increasing risks of cyber interference, algorithmic discrimination, and violation of farmers' privacy.

Thus, the current state of scientific research confirms the attention to artificial intelligence as an integrative basis for food network management, but indicates the absence of a complete AI-driven agri-logistics management framework that would combine technological, managerial, institutional, and environmental dimensions. This necessitates the formation of a conceptual model adapted to the requirements of digital food security in Ukraine and the global challenges of sustainable development.

3 METHODOLOGY

The purpose of the study is to summarize the current state of scientific developments at the intersection of artificial intelligence and logistics management in the agricultural sector, identify leading trends, intellectual dominants and scientific gaps, as well as form a conceptual model of AI-driven agri-logistics management, which integrates technological, managerial and environmentally sustainable dimensions of the digital transformation of agri-food supply chains.

Achieving the set goal involved solving the following research tasks: determining the dynamics of publication activity for 2008-2025; analyzing the structure of scientific cooperation (authors, countries, organizations, scientific journals); identifying key research clusters and areas of application of artificial intelligence in agri-logistics; systematizing the most intellectually influential works and their methodological approaches; summarizing scientific gaps and prospects for further research.

The methodological basis of the study is based on a combination of bibliometric analysis, systematic review of scientific publications and network mapping of knowledge. The search sample was formed in the Scopus database (Elsevier) using a combined query that combined key terms from three conceptual blocks: artificial intelligence (artificial intelligence, machine learning, big data analytics); logistics (logistics, supply chain management, routing, and inventory optimization); agricultural sphere or sector (agriculture, agri-food, food supply chain). The chronological boundaries of the analysis cover the years 2008–2025, which provides a tracing of the evolution of the research discourse from technical automation models to integrated strategic management solutions. In the primary sample, duplicates and irrelevant sources were eliminated according to the criteria of content relevance, the presence of agri-logistics and management components, as well as the availability of bibliographic metadata. As a result, the final array

included 27 scientific publications, which create a sufficient information base for identifying the intellectual structure of the research area.

At the second stage, quantitative and network analysis was applied using VOSviewer and the Bibliometrix (R) bibliometric package. Maps of co-publication interaction were constructed at the level of authors, countries and organizations, as well as networks of co-citation and co-use of key terms. This allowed us to identify structural research cores, thematic clusters and trajectories of changes in scientific priorities. Special attention was paid to the analysis of thematic evolution, which demonstrated a gradual transition from engineering-algorithmic models to integrated management solutions aimed at ensuring sustainability, traceability and energy efficiency of logistics processes.

The final stage was a qualitative interpretation of the revealed patterns, which included content analysis of the most cited and methodologically significant publications [11]-[17].

The generalization of their results and our own previous research [18]-[20] allowed us to form the basis of the conceptual model of AI-driven agri-logistics management, which involves the interaction of three levels:

1) technology (intelligent algorithms, machine learning, digital monitoring platforms);
2) organization (logistics processes, human resources competencies, innovative culture, risk management);
3) sustainability (energy efficiency, carbon footprint reduction, food security, transparency and traceability of supply).

The methodological reliability of the study is ensured by the interdisciplinary approach, the use of proven bibliometric tools, documentation of the stages of sample formation and adherence to ethical principles of scientific data processing. The main limitations are the dependence of the results on the specifics of the Scopus database, the different duration of the "citation life cycle" of new publications and the uneven representation of regional studies.

Given that the dataset is limited to Scopus-indexed publications, certain regional scientific schools may be underrepresented. Nonetheless, for identifying dominant structural patterns and intellectual clusters, Scopus provides a sufficiently reliable and consistent bibliographic basis.

The applied methodology allows not only to quantitatively outline the dynamics of scientific development of the topic, but also to identify intellectual centers, structural connections and research gaps that form the basis for further modelling of the transformation of agri-logistics based on artificial intelligence. The next section is devoted to the results of bibliometric analysis and interpretation of the identified scientific trends.

4 RESULTS

This section presents the results of bibliometric analysis and extensive interpretation, which serve as the basis for the formation of a conceptual model of AI-driven agri-logistics management. First, the network of co-occurrence of keywords was analyzed, which made it possible to identify a number of terminological clusters that reflect the main thematic areas of research.

On the network map of co-occurrence (Fig. 1), each node corresponds to a key term, and the links between them demonstrate the frequency of their joint use within one document; the thickness of the links indicates the intensity of such associations, and the grouping into clusters is displayed using different colours. As a result, ten interconnected clusters were identified, each of which represents a separate, but at the same time integrated aspect of the digital transformation of agri-logistics.

One of the most saturated clusters is associated with digital technologies in the agricultural sector. It includes keywords such as "Artificial Intelligence", "Machine Learning", "Big Data", "Internet of Things", "Blockchain", "Precision Agriculture", as well as terms reflecting general digitalization trends such as "Industry 4.0", "Automation", "Digitization". The joint appearance of "artificial intelligence" with "supply chain management" indicates the formation of a stable scientific core, in which AI is considered as a key tool for managing agri-food supply chains, focused on data analysis, automation and optimization of operations. It is in this cluster that forecasting models, machine learning algorithms for planning, as well as solutions related to the Internet of Things and sensor infrastructure are concentrated. The second significant cluster characterizes the research on supply chain management and ensuring their sustainability. The concepts "Logistics 4.0", "Supply Chain", "Resilience", "Performance", "Information Sharing", "Dual-Carbon" dominate here. They reflect the desire of researchers to combine digital technologies with approaches to increasing the efficiency and resilience of logistics systems in the face of climate, market and geopolitical risks. The emphasis on information exchange and carbon

aspects indicates the importance of transparency, reducing emissions and supporting the sustainability of agri-food chains.

A separate cluster is related to strategic management and information systems. The most common terms in this segment are “Strategic Management”, “Business Strategy”, “Decision Support Systems”, “Strategic Information Systems Planning”. It reflects research focused on developing strategies for the implementation of artificial intelligence, planning and development of information infrastructure, building decision support systems for agricultural logistics. In such works, AI is considered not only as a set of algorithms, but as an element of strategic changes that affects management models, organizational culture and institutional mechanisms.

Another important cluster concerns agri-food chains and innovations in agribusiness. The terms “Agri-Food”, “Agribusiness”, “Innovative Technologies”, “Digital Marketing”, as well as “Bibliometric” and “Systematic Literature Review” dominate here. This indicates a growing attention to comprehensive research on agri-food systems, innovative business models, digital marketing tools and bibliometric approaches to knowledge systematization. Within this direction, researchers focus on the transformation of agri-food chains, rethinking the interaction between producers, processors, logistics operators and end consumers.

The cluster dedicated to sustainable development and business models is also important. The keywords here are “Sustainability”, “Grand Challenges”, “Business Model”, “Business Model Innovation”, “Food Industry”. It reflects the efforts of the scientific community to integrate the principles of sustainable development into the concept of food industry management, the implementation of environmentally friendly and socially responsible business models based on digital solutions and intelligent analytics. Thus, a connection is formed in the scientific field between technological innovations and the transformation of the business logic of the functioning of agri-food systems.

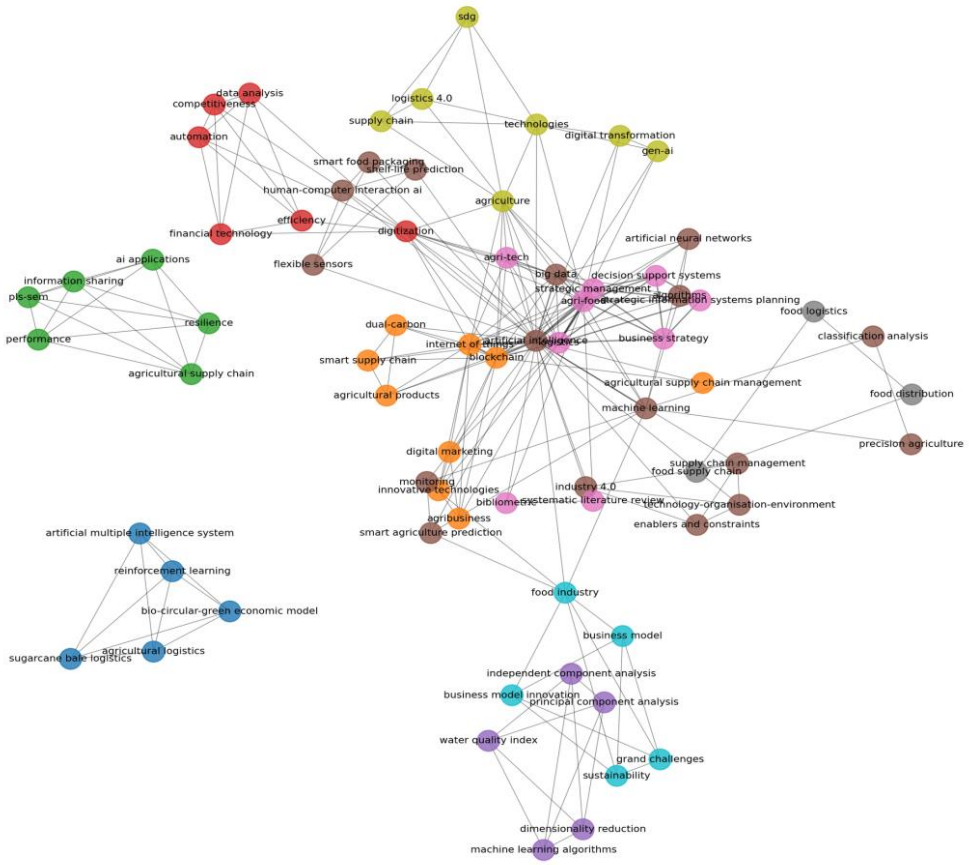


Figure 1: Keyword co-occurrence network (clusters highlighted in different colors).

A separate group is made up of specialized clusters that reflect narrowly focused research. For example, the cluster with the terms “Sugarcane Bale Logistics”, “Bio-Circular-Green Economic Model”, “Reinforcement Learning” illustrates the application of reinforcement learning in the logistics of the sugar industry and its connection with circular and “green” economic models. Another small cluster, which combines “Water Quality Index”, “Machine Learning Algorithms”, “Principal Component Analysis”, indicates the use of machine learning methods for monitoring and managing water quality in the agricultural sector. Such highly specialized areas complement the overall picture, demonstrating the breadth of application of AI in areas related to logistics.

Summarizing the analysis of the co-occurrence of keywords, it can be stated that the research field covers several interrelated areas: the implementation of AI and related digital technologies in the logistics processes of agricultural production; increasing the efficiency, sustainability and transparency of supply chains; strategic management of information systems and innovations in agribusiness; development of sustainable business models and solutions focused on minimizing losses and carbon footprint. The set of identified clusters forms a conceptual map of the research field, the center of which is the integration of artificial intelligence and logistics management of agri-food chains.

A temporal analysis of the development of the topic confirms the dynamic nature of the formation of this direction. As shown in Figure 2, the first single publications appear in 2008 and 2017, after which the activity remains low and uneven until 2019. Starting from 2019–2020, there is a steady increase in the number of publications, which turns into a rapid surge in 2025, when more than half of the entire array of analyzed works is published.

Such a jump correlates with the global explosive interest in artificial intelligence, generative models and their application in the field of logistics and agri-food systems. The growth of publication activity indicates the formation of a research community, the consolidation of digital agriculture development programs and the awareness of the strategic role of AI for food security.

The geographical structure of research confirms the international and distributed nature of the development of this topic. The analyzed publications involve authors affiliated with more than fifty scientific institutions in the world, with only two organizations having more than one publication.

Beijing Academy of Agriculture and Forestry Sciences is represented in two works, as is the University of Macedonia, known for its research in the field of bibliometrics and digital logistics. The remaining institutions are represented by single publications, among them are leading universities and scientific centers in China, Europe and other regions, such as Beijing Life Science Academy, National Tsing Hua University, Adam Smith Business School (University of Glasgow), etc. This picture indicates the absence of monopolization of the research field by one center and, at the same time, the formation of an extensive network of scientific groups.

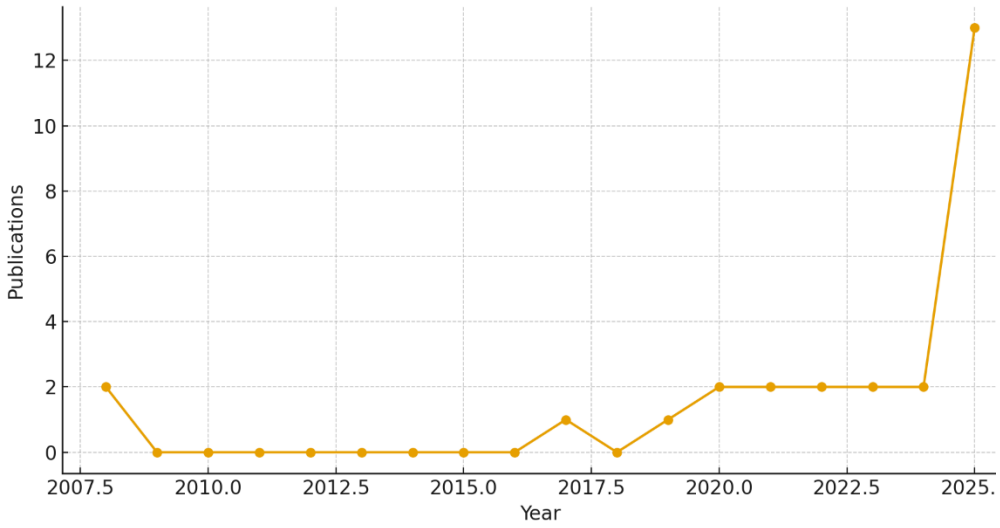


Figure 2: Dynamics of the number of publications on the selected topic by year.

The distribution of authorship by country is also quite diverse. In total, the participation of researchers from twenty-one countries was recorded. The leading positions in terms of the number of publications are occupied by Italy, China and India, for each of which the field of agri-food systems is of strategic importance. Several countries, including the United Kingdom, Ukraine, the United Arab Emirates, Jordan, Egypt, Oman, and Indonesia, have two publications each. As summarized, the range of key participants includes European and Asian states, as well as individual countries in the Middle East and Africa. This indicates, on the one hand, the global nature of the issue, and on the other, the different motives for its actualization: from the need for food security in countries with high dependence on imports to the aspirations of large agricultural economies to increase the efficiency and resilience of their own supply chains. To summarize the terminological field, a "word cloud" of the author's key terms was constructed (Fig. 3).

Although the USA is widely recognized as a global leader in AI research, it is underrepresented in our Scopus sample because many U.S. publications focus on general supply chain management rather than agricultural logistics specifically, and therefore did not meet the inclusion criteria.

The visualization shows the dominance of such concepts as "Artificial Intelligence", "Agri-Food", "Logistics", "Machine Learning", "Blockchain", "Strategic Management", which form the core of the research topic. Smaller terms, in particular "Resilience", "Sustainability", "Digital Marketing", "Precision Agriculture", reflect the specific emphases of individual studies related to sustainable development, precision agriculture and new communication tools in agribusiness. In general, the structure of the cloud confirms the multidisciplinary nature of the direction and the mutual interweaving of technological, managerial and industry aspects.

Based on the generalization of the dominant terms, their additional classification was carried out according to several semantic blocks (Table), which reproduce the logic of the research field. In particular, the technological cluster associated with the application of artificial intelligence algorithms for logistics needs (demand and yield forecasting, route optimization, inventory planning, anomaly detection); the transparency and trust cluster, which concentrates solutions based on blockchain, tracing systems, cold chain monitoring and product quality; the management cluster, focused on the framework for the implementation of digital technologies, risk management, and the maturity of organizational processes; the sustainability and energy efficiency cluster, which covers research on minimizing food losses, reducing emissions, and increasing resilience; and the data and integration cluster, which considers issues of data quality, system interoperability, cloud-edge processing, and IT solution integration architectures.

Each of these blocks is associated with certain types of tasks and methods – from regression models and deep learning to optimization algorithms, multi-criteria evaluation schemes and carbon accounting tools – as well as with expected effects in the form of cost reduction, logistics cycle times, loss reduction and increased system resilience.

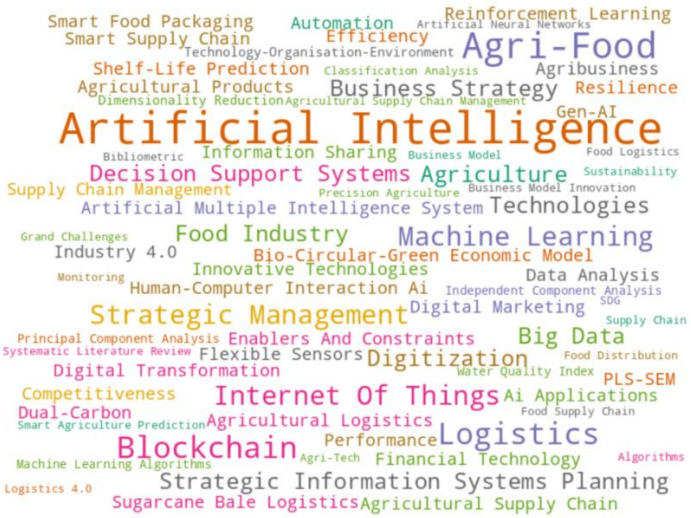


Figure 3: Author keyword cloud (the larger the word, the more often it occurs).

Table. Thematic clusters of key concepts in the research field “Artificial Intelligence and Logistics Management in the Agricultural Sector” (Scopus, 2008–2025).

Cluster	Core Keywords	Topic Extensions	Typical Tasks/Methods	Expected Effects
AI technologies for logistics	artificial intelligence; machine learning; deep learning; prediction; optimization	demand forecasting; routing; scheduling; inventory; anomaly detection	regression/gradient models; LSTM/GRU; ensemble methods; VRP heuristics; reinforcement learning	reduction of logistics costs and cycle time; higher forecasting accuracy; reduced food losses
Transparency and trust	blockchain; traceability; provenance; cold chain; quality monitoring	smart contracts; IoT sensors; HACCP integration	DLT; chain signature/hashing; event registries; integration with WMS/TMS	reduction of cold chain losses; improved compliance and auditability
Management frameworks and organizational change	supply chain management; S&OP; decision support; risk management; TOE	governance; data policies; ModelOps/MLOps; maturity models	multi-criteria decision models; process mapping; maturity assessment	shorter time-to-value; improved risk governance; scalability of AI solutions
Sustainability and energy efficiency	sustainability; food loss/waste; energy efficiency; CO_2; resilience	eco-design logistics; circularity; green KPIs	LCA/carbon accounting; IT energy-KPIs; network optimization	reduced emissions and food waste; enhanced supply chain resilience
Data and system integration	big data; data quality; interoperability; API; cloud-edge	ERP/WMS/TMS; telemetry; satellite; weather	data pipelines; feature store; data contracts	continuous data flows; model stability; increased system reliability

These clusters form a framework for a model where technological solutions are captured by organizational processes, and the result is measured by sustainable indicators.

As a result, bibliometric analysis allowed us to identify a structured system of knowledge about the research area: the latest trends, key thematic axes, active scientific centers and countries, as well as intellectual connections between the main concepts. Based on these results, a conceptual model of agri-logistics management based on artificial intelligence is proposed, which is designed to integrate technological, process and industry components into a single analytical field.

The proposed model (Fig. 4) considers the application of artificial intelligence in the logistics processes of the agricultural sector as a multi-level integrated system. Its core is formed by three interconnected areas: technological, covering digital algorithms, machine and deep learning systems, big data analytics, the Internet of Things, blockchain platforms and other AI tools; process, at the center of which is logistics management with its functions of planning, inventory management, optimization of transport routes, organization of warehousing and coordination between chain participants; and industry, which reflects the specifics of the agricultural sector – from primary production and processing to agri-food networks and relevant organizational structures. These three dimensions interact with each other through a system of "bridges" that represent specific points of application of AI in the logistics of agricultural production.

The conceptual model is based on several key principles. First, the principle of functional integration is implemented, according to which artificial intelligence does not act as an autonomous application, but is built into all main stages of the logistics cycle – from demand forecasting and resource planning to inventory management, route formation, supply control and end-user service.

Secondly, the principle of digital transformation of the agricultural sector is applied: logistics is considered as an information-rich process, where the movement of material flows is inseparable from the movement of data, and therefore, is subject to digitization, automation and intellectualization. Thirdly, the principle of sustainable development is taken into account, which involves the systematic processing of environmental, economic and social aspects of logistics solutions: artificial intelligence should not only increase efficiency, but also reduce

food losses, optimize resource use, contribute to reducing emissions and strengthening food security.

Fourthly, the model is based on the principle of adaptability and flexibility, when learning algorithms enable rapid response to changes in the external environment – weather fluctuations, price shocks, supply disruptions – and provide dynamic adjustment of logistics strategies in real time.

Structurally, the model assumes that the technological block of artificial intelligence covers a wide range of tools: from big data analytics and forecasting methods to deep neural networks, reinforcement algorithms, computer vision systems for product quality control, blockchain solutions for traceability and distributed event registries, as well as IoT sensor networks for monitoring fields, warehouses, transport and storage conditions. The logistics block includes the functions of supply and procurement planning, inventory and warehouse infrastructure management, optimization of transport routes and distribution, coordination of interaction between producers, processors, logistics operators and retail networks. The industry block focuses on the specifics of agricultural production, agri-food chains and the structure of agribusiness, which necessitates the consideration of seasonality, biological variability, climate risks and regulatory restrictions.

Within this architecture, the main functional areas of AI application are highlighted. These include forecasting yield, demand and price trends, which allows for more informed planning of production volumes and logistics flows; optimizing routes, schedules and the use of transport resources to reduce time, fuel and product quality losses; automating operations through the use of drones, robotic systems and sensor platforms for data collection and primary processing; real-time monitoring of the movement of goods and their storage conditions, which allows for timely identification of risks and intervention before significant deviations occur; ensuring traceability of agri-food products from producer to end consumer using blockchain platforms; and supporting solutions aimed at reducing food losses, managing the carbon footprint and increasing the overall sustainability of the supply chain.

The implementation of the model involves the participation of a wide range of stakeholders. For farmers and agribusinesses, it means access to forecasting tools and recommendation systems that help make more informed production and logistics decisions. Logistics operators gain the opportunity to apply intelligent routing systems, fleet management and transportation monitoring.

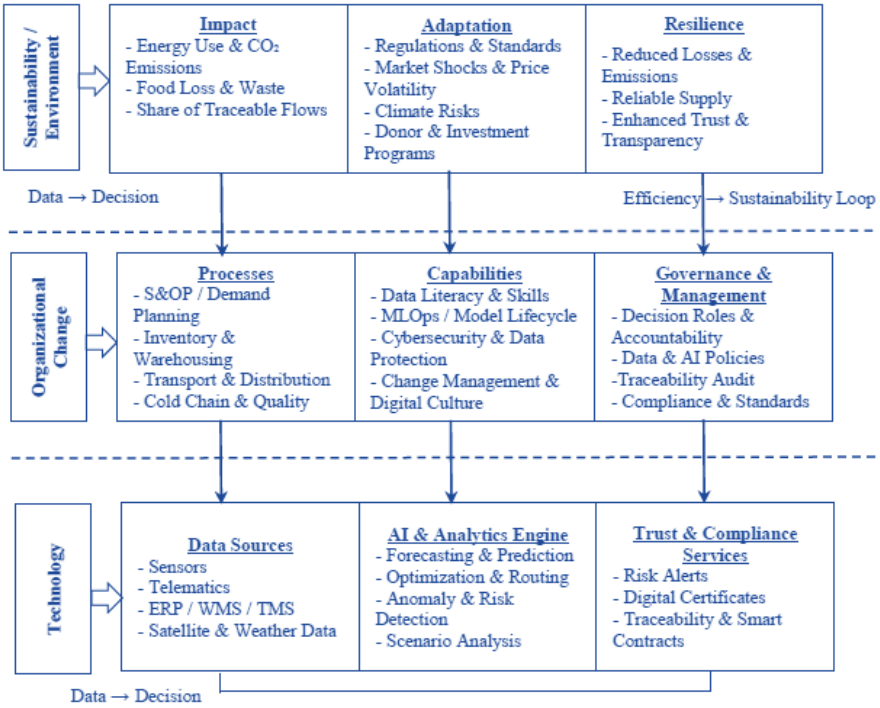


Figure 4: Conceptual model of ai-driven agri-logistics management [18-20].

Government authorities and regulators can use the model to develop smart agriculture policies and digital transformation of agri-food systems focused on food security and climate resilience. Research institutions and IT companies, in turn, act as developers of algorithms, digital platforms and analytical services, providing the scientific and technological basis for the functioning of the model.

The expected results of implementing the conceptual model are related to reducing transportation and storage costs, increasing the accuracy and reliability of supply, significantly reducing food losses and product damage in the supply chain, strengthening transparency and trust between participants in the agri-food network, as well as increasing the overall resilience of systems to external shocks. An important consequence is also the deepening of the digital transformation of agricultural logistics, which creates new opportunities for integration into global food chains and support for sustainable development goals. Thus, the result of the bibliometric analysis and further conceptual generalization is a model that not only describes existing research trends, but also offers a holistic theoretical and methodological framework for further empirical research and practical implementation of AI-driven agri-logistics management.

5 DISCUSSION AND RESEARCH LIMITATIONS

The results obtained demonstrate the growing relevance of research on the application of artificial intelligence in the logistics management of the agricultural sector, which is confirmed by the formation of an interdisciplinary scientific space at the intersection of digital technologies, supply chain management and sustainable development concepts.

The identified thematic clusters demonstrate the strengthening of the integration of machine learning and data analytics in the forecasting and optimization of logistics processes, the actualization of blockchain solutions to ensure transparency and traceability of agri-food chains, as well as the spread of research on risk management, decision-making and increasing the environmental sustainability of supplies. Such a structure of the scientific field indicates a gradual transition from isolated technical cases to a systemic conceptual understanding of digital agri-logistics as a key element of global strategies for sustainable, transparent and resilient food systems.

Comparison of the obtained results with the work of various leading scientists [11]-[15] gives grounds to assert that the majority of existing theoretical approaches focus on technological and organizational determinants of the implementation of artificial intelligence, but to a lesser extent reflect the environmental, energy and socio-economic consequences of the digital transformation of agri-food chains.

Even within the framework of popular theoretical frameworks, in particular the TOE-framework, the environmental, resource and carbon components of logistics remain auxiliary, which creates a noticeable imbalance between technological innovations and the principles of sustainable development. The conceptual model of AI-driven agri-logistics management proposed in the study is aimed at overcoming this discrepancy, combining three dimensions – Technology, Organization and Sustainability – into a holistic architecture focused on managing digital data flows, operational processes and performance indicators of the logistics activities of the agricultural sector.

Bibliometric analysis has shown an important shift in the focus of scientific research: from technical and algorithmic experiments and engineering solutions to assessing the impact of artificial intelligence on productivity, resilience, food security and energy efficiency of logistics networks. This trend indicates a transition to a more mature phase of the development of the scientific tradition, within which AI is considered not only as a tool for automation, but also as a strategic resource for the formation of adaptive, digital and low-carbon food systems.

It is important to note that the conceptual model proposed in this study remains analytical. Its practical applicability should be validated in future empirical research involving enterprise-level data, case studies, simulation modelling, or pilot implementations in agri-food supply chains.

Despite the results obtained, the study has a number of limitations that affect interpretation and can be taken into account in future works. First, the use of a single Scopus database leads to linguistic and regional selectivity, which may limit the representation of studies from countries that do not have established channels of scientific indexing, in particular, countries in Africa, Central Asia, the Middle East and regions affected by military or climate crises.

Secondly, the time lag of citations of new works (2024-2025) does not provide a complete assessment of their scientific impact, and therefore the results of the distribution by citations may be partially underestimated.

Thirdly, the difference in the indexing approaches of journals complicates the unification of author metadata and keywords, which may affect the accuracy of building network structures. Fourthly, the proposed conceptual model is of a theoretical and analytical nature and requires further validation based on applied cases, panel data of enterprises or simulation experiments.

Taking into account the above aspects determines the following trajectory of scientific research: the transition from descriptive and bibliometric description to empirical testing of the model at the level of enterprises, logistics clusters or national food systems.

This opens up prospects for expanding research in the areas of assessing the economic feasibility of implementing AI, developing methods for monitoring carbon footprints, integrating cybersecurity mechanisms, and analyzing informal institutions of trust in digital agro-logistics networks.

Given these challenges, the proposed results form the basis for the formation of more in-depth conceptual and managerial approaches that can be used in the future to develop intelligent decision support systems and new food and logistics security policies.

6 CONCLUSIONS

The conducted research allowed us to comprehensively characterize the current state and dynamics of the development of scientific publications dedicated to the application of artificial intelligence in the logistics management of the agricultural sector, as well as to identify the leading trends in the transformation of food chains in the direction of digital, transparent and environmentally sustainable agri-logistics.

The analysis of publication activity showed an exponential growth in the number of scientific developments after 2020, which indicates the emergence of a new interdisciplinary direction integrated into the global scientific discourse on sustainable and resilient food systems. The geography of author collaborations demonstrates the formation of a European-Asian center of scientific influence, which unites research groups from Italy, China, India, Great Britain and a number of other countries, while the participation of Ukraine, although still limited, indicates the prospects for the development of its own research school in the field of digital agri-logistics.

The identified cluster areas of the scientific field allow us to distinguish four conceptual dimensions of research:

1) technological, covering machine learning algorithms, big data analytics and intelligent decision support systems;
2) managerial, related to digital governance, supply coordination and risk management;
3) environmentally sustainable, which focuses on energy efficiency, reducing food losses and CO_2 emissions;
4) the dimension of transparency and trust, which is associated with the use of blockchain and traceability systems in agri-food chains.

The generalization of these areas formed the basis of the proposed conceptual model of AI-driven agri-logistics management, which combines three macro-levels – Technology, Organization and Sustainability – and provides a cyclical connection between data flows, management decisions and indicators of the effectiveness of logistics operations.

The practical results of the model provide grounds to argue that the implementation of AI in agri-logistics can provide significant operational, economic and environmental effects, in particular, reducing the time and costs of logistics operations, increasing the accuracy of routing and warehouse planning, reducing food losses and the carbon footprint of supplies, as well as increasing institutional transparency and trust between chain participants.

In view of this, it is advisable to formulate practical recommendations for different levels of logistics policy implementation. At the enterprise level, the priorities are the implementation of a centralized data management policy, the use of MLOps infrastructure, the launch of pilot projects on demand forecasting, route optimization and cold chain control, as well as the creation of KPI panels for assessing energy efficiency and CO_2 emissions.

At the industry level, standardization of traceability requirements, the development of public registers of “green” logistics initiatives and the stimulation of cluster cooperation between agricultural producers, research institutions and technology companies are important.

At the level of state policy, it is advisable to include digital agro-logistics in food security and energy resilience strategies, to involve EU funding

programs and international organizations (FAO, World Bank, IFC), and to create a national AI & Agri-Logistics Competence Center as a platform for knowledge transfer and best practices.

At the same time, the results of the study open up a number of prospects for further scientific work. Important areas of future research are the empirical validation of the conceptual model based on data from agricultural enterprises in Ukraine and EU countries, the development of regional indices of digital resilience of agro-logistics systems, the improvement of methods for quantitative assessment of the energy and carbon balance of the use of AI in food chains, the analysis of social trust in traceability systems and data cybersecurity, as well as the expansion of bibliometric analysis on Web of Science, Dimensions, and Google Scholar for deeper coverage of local scientific schools.

Solving these problems will contribute to the formation of a mature theoretical and applied platform for AI-oriented agri-logistics and strengthen the contribution of research to the implementation of strategies for the sustainable and safe development of food systems.

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IT-Driven Transformation of Global Trade and Its Impact on GDP in the Context of the 4IR

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Keywords: Global Trade, Gross Domestic Product (GDP), Export, Import, GDP Growth, Import Substitution, Structural Trade Shifts, Fourth Industrial Revolution (4IR), Industry 4.0, Digital Transformation, Digital Ecosystem, Digital Innovation, Digital Technologies.

Abstract: This study evaluates the impact of structural changes in exports and imports on GDP dynamics within the context of the Fourth Industrial Revolution (4IR), contrasting these effects with those observed during the Third Industrial Revolution. Using World Bank data for 1970-2021, the analysis shows that global trade peaked in 2008 at 61.43% of world GDP, followed by a gradual shift toward deglobalization driven by trade wars and import substitution policies. A comparative methodological approach is applied to examine GDP growth trajectories in relation to changes in the shares of exports and imports in GDP. The findings confirm that GDP growth rates are significantly influenced by both countries' income levels and structural trade shifts. The study demonstrates that 4IR amplifies GDP growth when export expansion outpaces import growth, while also increasing the volatility of GDP responses to structural changes in trade flows. Income-specific patterns are identified: low- and lower-middle-income countries tend to benefit from export-led substitution strategies, whereas upper-middle- and high-income countries gain more from balanced trade expansion. Future research will focus on exploring the role of artificial intelligence in shaping global economic growth.

1 INTRODUCTION

Today, the global economy is undergoing a rapid transition toward digital and smart technologies. This transition drives the intensification of digital transformation processes across modern ecosystems in the era of the Fourth Industrial Revolution (4IR), powered by information systems as well as digital and intelligent technologies [1] - [4].

Artificial intelligence, machine learning, blockchain, the Internet of Things, big data analytics, augmented and virtual reality, cloud computing, robotics, and digital twins are reshaping the rules of doing business and transforming how companies interact with customers and various stakeholder groups.

The digital economy has evolved from Industry 3.0 to Industry 4.0, which is characterized by qualitatively new features. Traditional companies are no longer the central actors in economic reality; instead, a new economic entity has emerged – the digital ecosystem. This stage of digital economic transformation involves integrating digital and smart technologies, innovative solutions, and advanced management approaches into all areas of activity. Such technological change requires companies to fundamentally transform their operations, customer relationships, and strategic management models.

These transformations contribute to the modernization and reorganization of business processes and business models within the Industry 4.0 paradigm.

It should be emphasized that the development of 4IR is closely interconnected with the evolution of global trade processes. From the standpoint of Schumpeterian economic theory, the Great Recession of 2007-2008 can be interpreted as a

"positive disruption" and as a marker of the transition from the Third to the Fourth Industrial Revolution.

Statistical analysis shows that in 2008, total exports and imports reached their maximum relative value of 61.43% of world GDP for the entire 1970-2021 period. After this point, the long-term upward trend in global trade – stable since the mid-1980s – was disrupted (Fig. 1) [5] - [7]. A new global trend began to emerge: deglobalization, marked by trade wars, reindustrialization, and import substitution. The synchrony between the onset of 4IR and the reversal of world trade dynamics suggests a hypothesis that the former may have influenced the latter.

Given this context, the present article examines the impact of global trade (including structural import substitution processes) on changes in GDP dynamics under the conditions of the Fourth Industrial Revolution.

2 LITERATURE REVIEW

Over the past decade, issues related to the development of the Fourth Industrial Revolution (4IR) have attracted considerable scholarly attention [8]-[16]. At the same time, the question of when the 4IR actually began remains open. There is no universal criterion for its determination, which is not surprising, as any historical periodization is inherently conditional. The boundaries between the First, Second, and Third Industrial Revolutions are also blurred.

By early 2016, however, the concept of the Fourth Industrial Revolution had already been clearly articulated, as evidenced by such publications as Industry 4.0 [17] and The Fourth Industrial Revolution [18]. This suggests that the processes identified by these authors had begun somewhat earlier.

As T. Philbeck and N. Davis noted, "the idea of 4IR is often taken to be a synonym for 'Industry 4.0', an initiative that emerged in Germany between 2011 and 2015, focusing on the application of digital technologies to manufacturing.

These two terms are not unrelated, but they describe different things. Industry 4.0 is an important component within the larger framing of 4IR, with its narrower, vital focus on the relationship between digitalization, organizational transformation, and productivity enhancement in manufacturing and production systems" [17]. During this period, a symbolic shift occurred in 2012, when a technology company (Apple) became the world's most valuable firm, surpassing ExxonMobil for the first time [20].

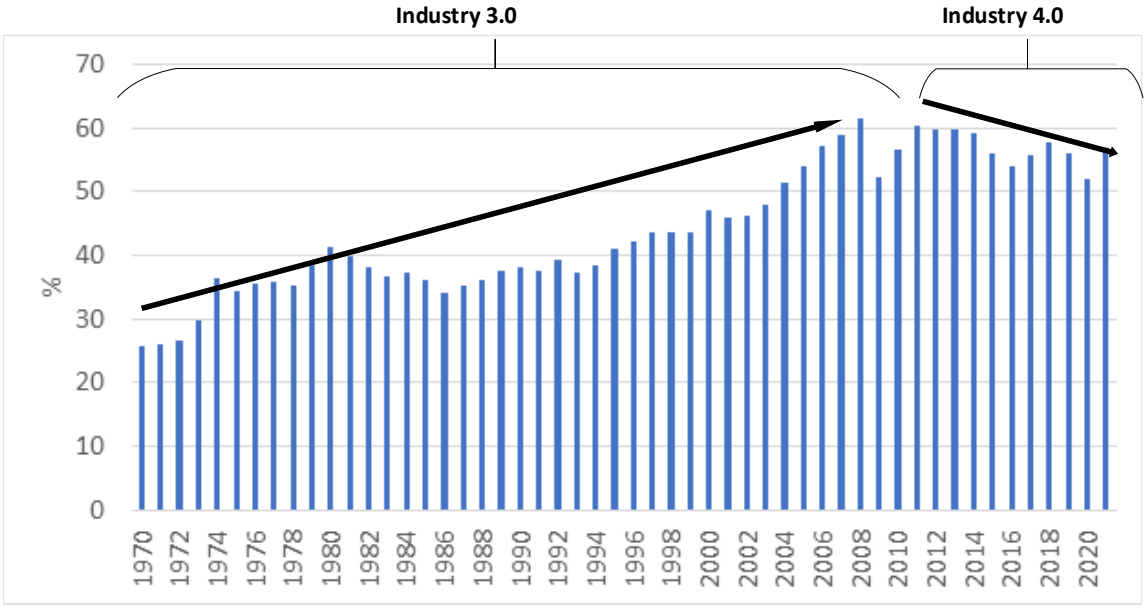


Figure 1: Exports and imports relative to world GDP in 1970-2021, %. Built on data [5] - [7].

This trend has only intensified. By mid-2024, the world's five most valuable companies were all technology firms (Microsoft, Apple, NVIDIA, Alphabet (Google), Amazon), with a combined market capitalization of nearly 14 trillion dollars. Meanwhile, ExxonMobil, once the leader, had fallen to 17th position [20].

The large-scale diffusion of new technologies has historically been associated with the redistribution of global economic power. During the transition from the Second to the Third Industrial Revolution, for example, leadership shifted from Great Britain to the United States.

Recent scholarship frequently employs such concepts as artificial intelligence, cyber-physical systems, big data, Industry 4.0, Industry 5.0, open innovation, Society 5.0, and the super-intelligent society. The transition from Society 4.0 to Society 5.0 is expected to be driven by the implementation of Internet of Things technologies, robotics, and big data, transforming society into an integrated smart environment (Society 5.0). The concept envisions the adaptation of services and industrial activities to the real needs of individuals, as well as the development of advanced digital platforms integrated into all spheres of life.

Researchers also emphasise that Industry 5.0 should not be viewed as a new industrial revolution but rather as an extension of Industry 4.0 technologies, achieved through increased collaboration between humans and intelligent machines. Within Industry 5.0, the nine core elements of Industry 4.0 are expanded by placing creativity and human well-being at the centre of industrial systems, thus combining the efficiency of machine technologies with human ingenuity.

A growing number of publications indexed in leading scientometric databases address these themes [21]-[28]. These works explore key characteristics and challenges for producers in the age of Industry 4.0 and 5.0, assess innovative models of adaptability for modernisation, and discuss long-term evolutionary trajectories such as the transition from Industry 4.0 to Nature 4.0 within the broader context of Society 5.0.

Some scholars also examine the relationship between 4IR development, global trade, and GDP. However, a search conducted in the Scopus database for 2009–2024 revealed only 12 publications that simultaneously addressed the keywords "Global Trade", "Gross Domestic Product", and "Industry 4.0/4IR/Fourth Industrial Revolution". The most frequently used keywords in the retrieved publications include: Gross Domestic Product, International Trade, Global Trade, Climate Change, Innovation, Environmental Impact, Urbanisation, and Theoretical Models.

The institutions most actively engaged in research on this topic include University College London; Tsinghua University; The Bartlett Faculty of the Built Environment; the International Institute for Applied Systems Analysis (IIASA); the Collaborative Innovation Center for Emissions Trading System; University of East Anglia; Univerzita Hradec Králové; Agricultural Research Council (Pretoria); the Ministry of Education of the PRC; and Zhejiang University. Most contributing authors are affiliated with China, the United Kingdom, the United States, Austria, Canada, the Czech Republic, Japan, Poland, South Africa, South Korea, and Switzerland. Notable contributions include works by M. Burri & T. Cottier [29]; C. M. T. Johnston & J. Buongiorno [30]; Y. Sun et al. [31].

Major funding organisations supporting research on the relationship between global trade and GDP in the context of Industry 4.0 include the National Natural Science Foundation of China; the UK Department for Business, Energy and Industrial Strategy; the Environmental Restoration and Conservation Agency; the Fundamental Research Funds for the Central Universities; the Japan Society for the Promotion of Science; the Ministry of Education, Culture, Sports, Science and Technology (Japan); the National Office for Philosophy and Social Sciences; the Natural Environment Research Council; the Science and Technology Research Partnership for Sustainable Development; and Zhejiang University.

Another group of scholars analyses the impact of structural changes in import substitution on GDP dynamics and economic growth. Among them are M. P. Abreu, S. A. Bevilacqua & M. D. Pinho [32]; A. R. Adewale [33]; J. A. Datas-Panero [34]; D. Irwin [35] - [36]; and A. Mendes, M. Bertella & R. Teixeira [37]. The problem of import substitution is particularly relevant in developing countries such as Pakistan, Indonesia [38], Chile [39], and Nigeria [40] - [41]. For instance, researchers in Nigeria argue that "the strategy of import substitution is relevant for rapid industrialization in the country" [40].

Despite these contributions, comparative studies analysing GDP growth trajectories against the backdrop of structural changes in export and import shares remain limited. Existing research predominantly focuses on the relationship between economic growth and the expansion of international

trade, while import substitution is usually examined solely within industrial sectors, overlooking the service sector. Moreover, few studies approach this issue from the standpoint of the macroeconomic structure of GDP, and the structural nature of import substitution remains largely understudied.

The transition to the Fourth Industrial Revolution has fundamentally reshaped global value creation, altering both the structure and geography of international trade. Digitalisation, artificial intelligence, automation, and advanced data analytics have enabled new forms of production, logistics, and services that diverge significantly from the patterns characteristic of Industry 3.0. Recent studies highlight that 4IR technologies reduce information asymmetries, improve supply chain efficiency, encourage reshoring and nearshoring, and stimulate the rapid expansion of digital services trade. These technological shifts influence the elasticity of GDP growth with respect to export and import dynamics, increasing both the speed and volatility of structural adjustments.

AI-driven supply-chain optimisation reduces transaction costs and supports more efficient resource allocation, enabling firms to adjust import needs and diversify export markets. Automation reduces dependence on offshore manufacturing, contributing to partial reindustrialization in high-income economies. Meanwhile, digital platforms and cloud-based services accelerate the growth of intangible exports, creating new sources of value for advanced economies while intensifying competition for middle-income countries. Consequently, the relationship between structural trade changes and GDP growth has become increasingly heterogeneous across income groups, reinforcing the need for differentiated empirical assessment.

In this regard, the structure of the present study involves two key stages: (1) demonstrating that GDP dynamics follow different trajectories depending on structural changes in the export and import shares of GDP; and (2) comparing GDP growth rates during the emergence of 4IR with the period dominated by the Third Industrial Revolution.

Therefore, the purpose of this study is to assess changes in GDP dynamics in the context of structural shifts in exports and imports during the development of the Fourth Industrial Revolution.

3 METHODOLOGY

Although this study relies on descriptive and comparative methods rather than regression modelling, such an approach is appropriate for analysing long-term structural trends over 1970–2021. Conducting regression analysis would require harmonised global panel data on structural breaks, technological adoption rates, and institutional differences – datasets that extend beyond the scope of this research. Instead, the comparative structural approach employed here allows the authors to identify generalisable patterns across income groups and industrial eras. This methodological choice is consistent with existing macro-comparative studies on long waves of technological change and global trade restructuring.

Traditionally, import substitution has been viewed as an instrument of industrialisation and economic growth. However, the key methodological challenge concerns how to “record” the occurrence of import substitution. At the micro level, this process is straightforward: goods and services previously produced or purchased abroad are subsequently produced and purchased domestically. At the macroeconomic level, however, this process is far less transparent.

Based on the classical expenditure approach to GDP:

$$Y = C + I + G + E_x - I_m, \quad (1)$$

where Y – Gross Domestic Product (GDP), C – consumption, I – investment, G – government spending, E_x – export, I_m – import.

At first glance, one might argue that, ceteris paribus, a decrease in imports should lead to an increase in GDP, and thus the maximisation of GDP would occur when imports approach zero and exports reach a maximum. However, this proposition is incorrect; the optimum exists under entirely different structural conditions.

Changes in the absolute values of imports also do not allow us to determine whether import substitution has occurred. For instance, a simultaneous decrease in both exports and imports cannot be interpreted as import substitution. Therefore, it is more appropriate to consider relative indicators – namely, changes in the shares of exports and imports in GDP.

Let us examine (1) at two moments in time, t and $t + 1$:

$$Y_t = C_t + I_t + G_t + E_{xt} - I_{mt}, \quad (2)$$

$$Y_{t+1} = C_{t+1} + I_{t+1} + G_{t+1} + E_{xt+1} - I_{mt+1}, \quad (3)$$

GDP growth between periods is defined as:

$$y_{t+1} = \frac{(Y_{t+1} - Y_t)}{Y_t}, \quad (4)$$

Export and import shares in GDP at time t:

$$exp_t = \frac{E_{xt}}{Y_t}, \quad (5)$$

$$imp_t = \frac{I_{mt}}{Y_t}, \quad (6)$$

Changes in export and import shares:

$$\Delta exp_{t+1} = exp_{t+1} - exp_t, \quad (7)$$

$$\Delta imp_{t+1} = imp_{t+1} - imp_t \quad (8)$$

Thus, the main hypothesis of this study is that the GDP growth rate (y_{t+1}) depends on changes in exports and imports in GDP structure (Table 1).

In this research, a strong quantitative criterion of import substitution is defined as a decrease in the import share in GDP accompanied by an increase in the export share. A weak quantitative criterion is defined as a decrease in both import and export shares in GDP, with the decrease in imports exceeding the decrease in exports.

The statistical basis of the study consists of World Bank data:

1) Exports of goods and services (% of GDP) [5];
2) Imports of goods and services (% of GDP) [6];
3) GDP growth (annual %) [42];
4) World Trade Statistical Review 2021 [7].

Data extraction and pre-processing were performed using a Python-based program capable of analysing large datasets, visualising trends, applying machine learning techniques, and automating data-processing routines.

The principal method applied in this study is comparative analysis. It is used to compare GDP dynamics under conditions of structural changes in export and import shares. The analytical logic progresses from general global patterns to specific income-group trajectories.

Table 1: Options for structural import substitution (changes in exports and imports).

Option	In the GDP structure		Description of the option from the perspective of import substitution
	Export	Import	
1	Increase $\Delta exp_{t+1} > 0$	Increase $\Delta imp_{t+1} > 0$	
1.1	The share of exports is growing faster than the share of imports ($\Delta exp_{t+1} > \Delta imp_{t+1}$)		Harmonious structural import substitution (by export) is taking place
1.2	The share of exports is growing at the same level as the share of imports $\Delta exp_{t+1} = \Delta imp_{t+1}$		The status quo is maintained
1.3	The share of exports is growing more slowly than the share of imports $\Delta exp_{t+1} < \Delta imp_{t+1}$		Structural export substitution (by import) is taking place
2	Increase $\Delta exp_{t+1} > 0$	Decrease $\Delta imp_{t+1} < 0$	Active (effective) import substitution is taking place
3	Decrease $\Delta exp_{t+1} < 0$	Increase $\Delta imp_{t+1} > 0$	Export substitution by import is taking place
4	Decrease $\Delta exp_{t+1} < 0$	Decrease $\Delta imp_{t+1} < 0$	
4.1	Exports are falling faster than imports in the GDP structure ($\Delta exp_{t+1} < \Delta imp_{t+1}$)		Passive (negative) export substitution occurs
4.2	Imports are falling faster than exports in the GDP structure ($\Delta exp_{t+1} > \Delta imp_{t+1}$)		Passive (negative) import substitution is taking place
4.3	Imports and exports in the GDP structure decrease equally ($\Delta exp_{t+1} = \Delta imp_{t+1}$)		The status quo is maintained

4 RESULTS

The dynamics of import changes in the GDP structure, at first glance, agree with the dynamics of the GDP itself (Fig. 2). However, this is not the case. The correlation coefficient between the dynamics of GDP and the structural dynamics of exports (imports) is only 60%. The synchronicity of structural changes in exports and imports is observed only at the global level.

Table 2 shows the number of cases of structural changes in exports and imports.

Table 2: The number of cases falling into each of the quadrants of structural change in exports and imports.

Export	Import	
	Decrease $\Delta imp_{t+1} < 0$	Increase $\Delta imp_{t+1} > 0$
Increase $(\Delta exp_{t+1} > 0)$	1280 (16%)	2947 (36.84%)
Decrease $\Delta exp_{t+1} < 0$	2421 (30.26%)	1352 (16.90%)

As presented in Table 2, in 2421 cases there is a trend of reduction in exports and imports. The largest group (2947 cases) shows simultaneous growth in both exports and imports, which might suggest overall trade expansion.

The calculations given in Table 3 prove that the value of average GDP growth is significantly influenced by structural changes in exports and imports. At the same time, the greatest GDP growth is observed when the share of exports increases and the share of imports decreases. As the calculations show, under such conditions, the average GDP growth is 4.17%. Under conditions of a simultaneous increase in the share of exports and imports, the average GDP growth is estimated at 3.98%. On average, under conditions of an increase in the export share and a decrease in the import share, as well as a simultaneous increase in both export and import shares, GDP growth is 4.38% and 4.68%, respectively (Table 4).

The highest GDP growth is observed in cases involving countries with upper middle income or high income levels and a simultaneous increase in the shares of exports and imports (Table 4). In these cases, the average annual GDP growth is 5.61%.

Table 3: Average GDP growth under conditions of structural change in exports and imports, *%*.

Export	Import	
	Decrease $\Delta imp_{t+1} < 0$	Increase $\Delta imp_{t+1} > 0$
Increase $(\Delta exp_{t+1} > 0)$	4.17	3.98
Decrease $\Delta exp_{t+1} < 0$	2.75	3.72

With a middle income level, an increase in the export share and a decrease in the import share, the average GDP growth is slightly lower but still significant, at 5.41%. It is important to note that for countries with high income or upper middle income levels, the maximum GDP growth is achieved with a simultaneous increase in exports and imports within the GDP structure. For other countries, with middle income, lower middle income, or low income levels, the optimal approach for ensuring economic growth is an increase in exports in the structure alongside a structural decrease in imports.

It is also necessary to highlight that for countries with middle income, lower middle income, or low income levels, a simultaneous decrease in both exports and imports in the structure is more preferable (from the perspective of GDP growth) than a structural decrease in exports under conditions of structural import growth. For example, for countries with middle income, in the first case, GDP growth is 4.4%, while in the second, it is 3.75%. For countries with high income or upper middle income levels, the situation is diametrically opposite. Thus, for high income countries in the case ($\Delta exp_{t+1} < 0$; $\Delta imp_{t+1} > 0$), GDP growth is 3.18%, while in the case ($\Delta exp_{t+1} < 0$; $\Delta imp_{t+1} < 0$), it is significantly lower, at only 1.24%.

Thus, it can be stated that the income level and structural changes in exports and imports have a substantial impact on GDP growth, and there are different growth patterns for two groups of countries.

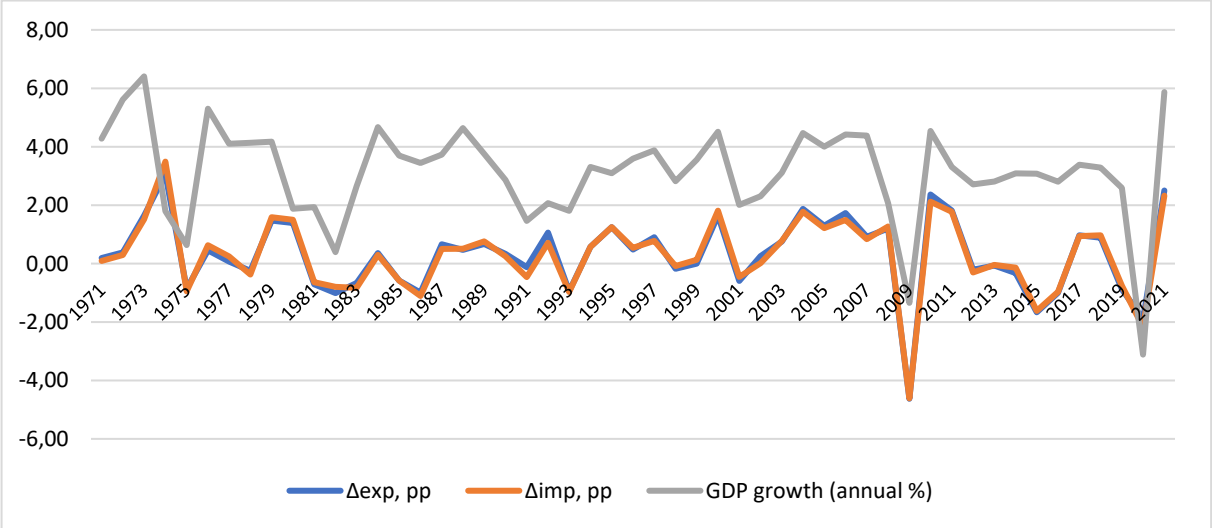


Figure 2: GDP growth, exports and imports relative to world GDP in 1970-2021, %. Built on data [5] - [7].

Table 4: Average GDP growth depending on the average income level under conditions of structural change in exports and imports, %.

Income level	$\Delta exp_{t+1} > 0$ $\Delta imp_{t+1} < 0$	$\Delta exp_{t+1} > 0$ $\Delta imp_{t+1} > 0$	$\Delta exp_{t+1} < 0$ $\Delta imp_{t+1} > 0$	$\Delta exp_{t+1} < 0$ $\Delta imp_{t+1} < 0$
1. High income	1.80	3.27	3.18	1.24
2. Upper middle income	5.15	5.61	4.81	4.62
3. Middle income	5.41	5.24	3.75	4.40
4. Lower middle income	4.97	4.92	3.17	3.83
5. Low income	4.54	4.38	3.04	3.68
Average	4.38	4.68	3.59	3.55

The first group includes countries with upper middle income or high income levels, while the second includes countries with middle income, lower middle income, or low income levels. The change in growth patterns occurs during the transition from middle income levels to upper middle income levels.

As shown in Table 5, the scenario of a structural increase in exports alongside a decrease in imports is most typical for countries with middle income or lower middle income levels. It is least typical for countries with high income levels.

The scenario of a simultaneous increase in the shares of exports and imports within the GDP structure is most typical for countries with high income levels. It is least typical for countries with low income levels.

The scenario of a decrease in exports in the structure alongside an increase in imports is most typical for countries with lower middle income levels. It is least typical for countries with high income levels.

The scenario of a simultaneous decrease in the shares of exports and imports within the GDP structure is most typical for countries with upper middle income levels. It is least typical for countries with low income levels.

The study illustrates (Table 6) that, without accounting for structural changes in exports and imports, GDP growth was faster under the conditions of Industry 3.0 than under Industry 4.0 (3.91% and 2.5%, respectively). However, the maximum growth during the era of Industry 3.0 occurs in scenarios of structural export growth alongside a reduction in the import share within the GDP structure, reaching 4.46% annually. In the era of Industry 4.0, the emphasis shifts. The highest growth is observed in countries where the share of exports grows faster than the share of imports.

Table 5: The Distribution of Observations by Income Level in the Context of Structural Changes in Exports and Imports within GDP.

Income level	$\Delta exp_{t+1} > 0$ $\Delta imp_{t+1} < 0$	$\Delta exp_{t+1} > 0$ $\Delta imp_{t+1} > 0$	$\Delta exp_{t+1} < 0$ $\Delta imp_{t+1} > 0$	$\Delta exp_{t+1} < 0$ $\Delta imp_{t+1} < 0$
1. High income	2 (6.9%)	31 (26.5%)	2 (10%)	16 (18.6%)
2. Upper middle income	7 (24.1%)	25 (21.4%)	5 (25%)	23 (26.7%)
3. Middle income	8 (27.6%)	27 (23.1%)	3 (15%)	22 (25.6%)
4. Lower middle income	8 (27.6%)	23 (19.7%)	7 (35%)	16 (18.6%)
5. Low income	4 (13.8%)	11 (9.4%)	3 (15%)	9 (10.5%)
Total	29 (100%)	117 (100%)	20 (100%)	86 (100%)

Table 6: GDP growth depending on the direction and speed of structural change in exports and imports, *%.*

Option	In the GDP structure		Industry 3.0 (before 2011)	Industry 4.0 (2012-2021)
	Export	Import		
	Without taking into account the structure of exports and imports		3.91	2.50
1	Increase $\Delta exp_{t+1} > 0$	Increase $\Delta imp_{t+1} > 0$	4.07	3.60
(1.1)	The share of exports is growing faster than the share of imports ($\Delta exp_{t+1} > \Delta imp_{t+1}$)		4.08	3.75
(1.2)	The share of exports is growing more slowly than the share of imports $\Delta exp_{t+1} < \Delta imp_{t+1}$		4.06	3.50
(1.3)	The share of exports is growing at the same level as the share of imports $\Delta exp_{t+1} = \Delta imp_{t+1}$		n/d	n/d
2	Increase $\Delta exp_{t+1} > 0$	Decrease $\Delta imp_{t+1} < 0$	4.46	3.09
3	Decrease $\Delta exp_{t+1} < 0$	Increase $\Delta imp_{t+1} > 0$	4.19	1.94
4	Decrease $\Delta exp_{t+1} < 0$	Decrease $\Delta imp_{t+1} < 0$	3.22	1.56
(4.1)	Imports are falling faster than exports in the GDP structure ($\Delta exp_{t+1} > \Delta imp_{t+1}$)		3.07	2.14
(4.2)	Exports are falling faster than imports in the GDP structure ($\Delta exp_{t+1} < \Delta imp_{t+1}$)		3.42	0.72
(4.3)	Imports and exports in the GDP structure decrease equally ($\Delta exp_{t+1} = \Delta imp_{t+1}$)		n/d	1,49*

Notes: * one observation.

In the most disadvantageous position during the era of Industry 4.0 are countries where exports fall faster than imports in the GDP structure. The average annual GDP growth in such cases is 0.72%. The analysis of deviations from average GDP growth rates shows that the transition from Industry 3.0 to Industry 4.0 is characterized by a significant increase in volatility in the context of structural changes. Specifically, the coefficient of variation under Industry 4.0 more than doubled compared to Industry 3.0, rising from 1.39 to 3.03 percentage points (Table 7).

Accordingly, the maximum positive deviation in the era of Industry 3.0 was 0.55 percentage points, while in Industry 4.0 it was 1.25 percentage points. The maximum negative deviations were -0.84 percentage points and -1.78 percentage points, respectively. Thus, against the background of slowing economic growth, the role of structural changes in exports and imports within GDP has strengthened.

5 DISCUSSION AND LIMITATIONS OF THE RESEARCH

The empirical findings indicate that the transition from Industry 3.0 to Industry 4.0 has substantially reshaped the relationship between export–import structures and GDP growth. These results should be interpreted in the context of current research on digital transformation, global value chains, and technological restructuring.

Table 7: Deviation from average GDP growth depending on the structural change in exports and imports, *p.p.*

Option	In the GDP structure		Industry 3.0 (before 2011)	Industry 4.0 (2012-2021)
	Export	Import		
1	Increase $\Delta exp_{t+1} > 0$	Increase $\Delta imp_{t+1} > 0$	0.16	1.10
(1.1)	The share of exports is growing faster than the share of imports ($\Delta exp_{t+1} > \Delta imp_{t+1}$)		0.17	1.25
(1.2)	The share of exports is growing more slowly than the share of imports $\Delta exp_{t+1} < \Delta imp_{t+1}$		0.15	1.00
(1.3)	The share of exports is growing at the same level as the share of imports $\Delta exp_{t+1} = \Delta imp_{t+1}$		n/d	n/d
2	Increase $\Delta exp_{t+1} > 0$	Decrease $\Delta imp_{t+1} < 0$	0.55	0.59
3	Decrease $\Delta exp_{t+1} < 0$	Increase $\Delta imp_{t+1} > 0$	0.28	-0.56
4	Decrease $\Delta exp_{t+1} < 0$	Decrease $\Delta imp_{t+1} < 0$	-0.69	-0.94
(4.1)	Imports are falling faster than exports in the GDP structure ($\Delta exp_{t+1} > \Delta imp_{t+1}$)		-0.84	-0.36
(4.2)	Exports are falling faster than imports in the GDP structure ($\Delta exp_{t+1} < \Delta imp_{t+1}$)		-0.49	-1.78
(4.3)	Imports and exports in the GDP structure decrease equally ($\Delta exp_{t+1} = \Delta imp_{t+1}$)		n/d	-1.01
Range of variation			1.39	3.03

First, the observed increase in GDP growth volatility under 4IR can be attributed to accelerated technological diffusion and digitalisation. AI-driven optimisation improves responsiveness to market fluctuations but simultaneously heightens exposure to global disruptions, including supply-chain bottlenecks, geopolitical tensions, and technological shocks. This dual effect contributes to the higher coefficient of variation documented in the study.

Second, the results reveal two distinct growth models. High-income and upper-middle-income economies benefit most from a balanced expansion of both exports and imports. This aligns with their deep integration into global value chains, where they rely on technologically sophisticated intermediate imports while exporting high-value-added goods and digital services. Their comparative advantage is rooted in innovation capacity, digital platforms, and advanced manufacturing systems.

In contrast, middle-income and low-income economies exhibit stronger GDP growth under export-led substitution, particularly when import shares decline. This reflects ongoing efforts to strengthen domestic production capacity, reduce dependence on imported intermediates, and leverage cost or resource advantages. However, for these economies, AI and automation may generate additional challenges by shifting global production toward more technologically advanced centres, increasing the need for targeted export development strategies.

Third, the structural break associated with 4IR suggests that global trade has become more sensitive to technological disruptions. Automation, robotics, and digital platforms reshape comparative advantages more rapidly than in previous industrial eras, making the structural composition of trade flows a critical determinant of macroeconomic performance.

Several limitations of the study should be acknowledged:

1) The analysis does not include regression modelling, lag structures, or instrumental variables; therefore, causal inference remains limited.
2) The use of aggregate country-level data does not allow for capturing micro-level mechanisms of 4IR adoption, such as firm-level productivity or sectoral digitalisation.
3) The Industry 4.0 period (2012–2021) is relatively short and includes major shocks such as the COVID-19 pandemic, which may distort long-term structural patterns.
4) The study does not differentiate between types of exports (goods vs. services), despite the fact that 4IR disproportionately accelerates the growth of digital services.

These limitations highlight promising directions for future research, particularly in expanding the analysis through econometric modelling, sectoral decomposition, and firm-level datasets.

6 CONCLUSIONS

The results of the study allow for several key conclusions.

1) The term import substitution is widely used in the academic literature, as evidenced by a substantial body of research in economic theory and international economic relations. Although conceptually well-established, its macroeconomic measurement remains methodologically challenging.
2) The findings confirm the hypothesis that GDP growth rates depend on structural changes in the shares of exports and imports. The analysis demonstrates that GDP dynamics follow different trajectories depending on the direction and magnitude of these structural trade shifts. High-income countries are characterised by simultaneous increases in both export and import shares within the GDP structure, reflecting their integration into global value chains.
3) The study compares GDP growth patterns during the emergence of the Fourth Industrial Revolution with those observed during the period dominated by Industry 3.0. The comparison reveals important structural differences in how economies respond to changes in trade composition.
4) The results show that structural substitution of imports by exports is associated with more dynamic GDP growth relative to long-term averages. The Fourth Industrial Revolution affects GDP growth not only by accelerating technological transformation but also by increasing volatility. This is reflected in a more than twofold rise in the coefficient of variation (from 1.39 to 3.03 percentage points), indicating greater sensitivity of GDP growth to structural trade adjustments.

Future research will extend this work by examining the impact of artificial intelligence technologies on economic growth across countries with different income levels and technological trajectories.

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Human Factor as a Determinant of Technology Development and Economic Growth in the Period of Digital Transformation

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Abstract: The active deepening of transformation processes has led not only to the introduction of digital technologies, but also significantly increased the role of the human factor. The deployment of the fourth industrial revolution has contributed to the formation of a new technological paradigm, which digital technologies act as the basis for the economics' modernization. The driving force of these processes remains a person who not only produces technological innovations, but also effectively uses them. In this context, special attention is paid to the study of theoretical aspects of the relationship between the human factor and human capital, as well as empirical confirmation of the influence of a person on the country's innovative capacity. Accordingly, the purpose was to reveal the relationship between human capital and the human factor, as well as to clarify their significance in the formation of innovative potential and economic growth in the context of the digital transformation. The various methods of cognition were used, including comparative analysis, graphic method, system approach and correlation analysis. As a result of the study, it was found that behavioral factors as the basis of the human factor cannot be considered in isolation, because they are formed based on human capital and reflect its practical implementation. Only in the interaction two components is the human potential revealed, which can ensure the stability and effectiveness of social development. The correlation analysis conducted confirmed the presence of a close relationship between the level of human capital and the innovative capacity. It was found that improving the quality of human capital contributes to strengthening the innovative potential and advancing the state in the world rankings of innovative development. This indicates that human capital acts as a system-forming factor of innovation processes and determines the strategic opportunities for economic growth.

1 INTRODUCTION

The modern development of society is determined by active transformational processes that cause the rapid spread of digital technologies, which implementation causes a change in the technical and technological structure, modification of the mechanisms for achieving economic growth and contributes to the gradual increase in the role of the human factor as a key determinant of development. Taking into account such changes, it can be stated that today the national economies of the world's leading countries are in a state of digital modernization, which occurs under the influence of the fourth industrial revolution and involves the widespread use of Big Data, artificial intelligence, machine learning, the Internet of Things, analytics, automated systems and robotics, which radically change the characteristics of management, tools and mechanisms for achieving goals, forming new conditions for ensuring sustainable economic development.

These processes bring to the fore a person and his human capital with all its qualitative characteristics, which become a driver kind of innovation creation and their transformation into effective technological solutions. Indeed, only a person as a carrier and owner of skills, abilities, knowledge and innovative potential in general, can generate technological

innovations and subsequently transform them into effective tools, which will allow to increase the competitiveness of the national economy and strengthen its position on the world stage.

Even though digital technologies are a kind of basis for the modernization of the economy and society, their effective use is determined by human. Accordingly, technologies are not a self-sufficient source of development, they only play the role of a tool (a modernized tool of labor), which effective use depends on the level of competencies, value system, worldview and culture of its users. Thus, in interaction with technologies, a person can act as both a direct user and a developer or creator of new solutions. Therefore, it is human who not only generates innovations and creates new technological solutions, but also sets the vector of their use and further development. The consequences of this process can be both positive, which is manifested in promoting the growth of productivity and efficiency, and have destructive manifestations, among which we highlight the aggravation of the risks of digital inequality, the displacement of traditional forms of labor by automated systems, the growth of social disunity or structural fragmentation of society.

The outlined trends confirm the need for an in-depth scientific analysis for the role of the human factor in the period of technological change. We believe that the results of such studies can serve as the basis for the formation of effective state policy in the field of digital economy development, the development of human capital and its adaptation to the new requirements of the time, as well as for the development of new models of human-technology interaction. Therefore, the comprehensive disclosure of the human factor as a determinant of technology development in the period of digital transformation of the national economy is an extremely relevant and mature issue in both theoretical and practical dimensions.

2 LITERATURE REVIEW

Recent trends in economic progress in developed countries have led to an increase in interest among the scientific and research community in substantiating how digital technologies change business, economics, education and society. In this aspect, special importance is attached to the disclosure of the issue for the human factor in the context of digital transformation, which is reflected in numerous theoretical and empirical publications. In particular, such developments are devoted to the analysis for the role of human capital in the implementation and using digital technologies; identifying the features of the interaction between humans and technologies; studying the processes of forming digital culture, consciousness, thinking and qualitative characteristics of human capital, which are due to technological changes; revealing organizational, managerial and institutional aspects aimed at the development of the human factor.

Thus, recently, there has been an increase in the number of scientific publications that widely use keywords such as "digital skills", "human factor in digital transformation", "ICT usage", "labor structure in digital economy". Among them, the most popular research category is digital skills, which is primarily due to their decisive importance in ensuring the efficiency of the functioning for the digital economy and the competitiveness of human capital. In particular, the scientific work of Ester van Laar [1] deserves attention, which emphasizes that innovations begin with a person. In the conditions of the dynamic development of the modern knowledge economy, it is digital skills and 21st century skills, which the authors consciously distinguish, that determine the competitiveness of the organization and its innovative potential. It is also worth noting separately that the presented understanding of 21st century skills is broader than digital, which is due to the inclusion of ethical awareness, cultural awareness, flexibility, self-direction and lifelong learning in their composition. It is especially appropriate to emphasize the results of the study by Tsyra O. [6], which states that digital transformation changes the requirements for human skills, abilities and knowledge. This, in turn, actualizes the development of digital skills, which level depends on the development of the national economy and its competitiveness, as well as the activity of implementing and spreading innovative activities.

In Qi Xiong's study [2], digital transformation is defined not only as a technological replacement, but as a process of achieving efficiency, which becomes possible due to the complementarity and integration of human and machine. The authors also emphasize that the model's development of such interaction is due to the widespread use of intelligent systems, in particular robots, computers, artificial intelligence algorithms and automated control systems.

In general, an approach that combines the analysis of human capital and digital technologies as interrelated factors of economic development is becoming increasingly widespread in scientific research. As an example, we can cite the work of Popelo O. [8], which reveals the role of digital

technologies in balancing the labor market and determines the importance of digitalization in the formation of new opportunities for professional human realization. We believe that such an approach allows us to consider a person not only as a user of new technologies, but also as an active subject capable of generating trajectories of economic transformation.

In addition, a significant number of review studies on this issue deserve attention. In particular, the works of Maria Anna Lykourentzou [3] emphasize the human factor as a factor that allows achieving success in digital transformation projects. The work of Pablo Reyes-Cornejo [4] records the growth of scientific interest in substantiating the role of flexible skills in the processes of change caused by the spread of digital technologies and emphasizes the analysis of digital transformation through the prism of human resource management in the context of personnel policy, which is considered as the basis for the formation of new skills. Another work by Daniela-Aida Ionescu [5] emphasizes that digital transformation encompasses two complementary dimensions: technological, which provides tools; human, which determines the reality and effectiveness of changes. The authors conclude that the long-term success of digital transformation directly depends on managing the process of integrating technology with human potential. The systematic review presented in the study by Jelena Crnobrnja [7] identifies the feasibility of using a systemic approach to provide a more comprehensive analysis of human-centricity in the context of Digital Transformation and Industry 5.0. Special attention is also paid to the issue of harmonizing technological development with human values, safety, ergonomics, skills development and ensuring employee well-being.

Thus, a review of modern scientific developments shows that a person is a key condition for the development of technologies during the period of digital transformation of the national economy. After all, firstly, it is a person who becomes the central element of the digital environment, and the effectiveness of integrating innovations into various spheres of social production depends on the level of knowledge, skills, competencies and flexibility of adaptation. Secondly, coordinating the interaction of a person and technology requires not only technical, but also social, ethical and organizational solutions that ensure the harmonious coexistence of artificial intelligence, automation and human capabilities. Thirdly, modern research emphasizes the need to clearly define the role of a person in the development and use of new technologies, from a creative subject capable of generating innovative ideas to a bearer of values, security and responsibility in the digital space. We believe that in this context, further scientific research should be aimed at using interdisciplinary and systemic approaches that will reveal the human factor as the leading determinant of the development and use of modern technologies during the period of digital transformation of the national economy.

3 SYSTEMIC INTERCONNECTIONS OF THE HUMAN FACTOR AND HUMAN CAPITAL

In our study, we proceed from the premise that the human factor is a derivative manifestation of human capital, even though, as a rule, they are considered in different analytical dimensions. The human factor is mostly used in socio-psychological and organizational-management aspects, which allow to focus on the personal characteristics and behavioral reactions of the individual. Human capital is one of the most studied economic categories of modernity, reflecting the qualitative parameters of a person in the form of a resource that can be accumulated, multiplied and converted into added value. However, there is an internal connection between these categories: human capital is basic, and the human factor is a superstructure or a derivative category that reflects the practical use of the accumulated potential.

We believe that the most generally accepted definition of "human capital" is the approach presented by the OECD, according to "Human capital can be broadly defined as the stock of knowledge, skills and other personal characteristics embodied in people that helps them to be productive" [10]. That is, human capital accumulates in knowledge, skills, qualifications, professional experience, appropriate health status, cultural level and value system, and forms the potential for personal development. However, such potential does not guarantee the effective course of socio-economic processes. Since it acquires real significance only when it is reflected in the practical activities of a person. Accordingly, at this stage, human capital is transformed into a factor or force that directly affects the effectiveness of production, management or social relations (Fig. 1).

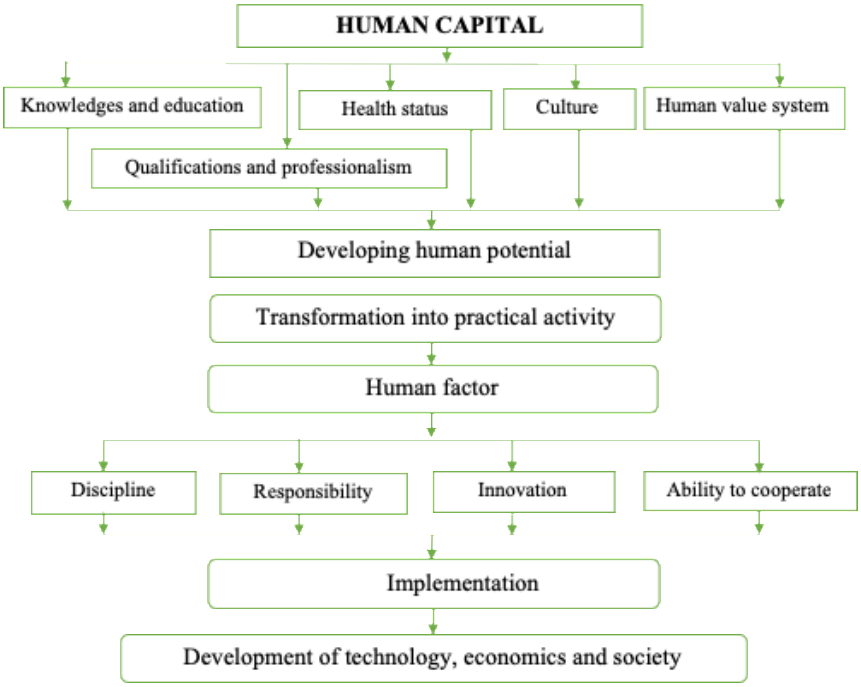


Figure 1: Structure and components of human capital as the basis for personal development potential.

Therefore, discipline, responsibility, innovation and teamwork, which are attributed to the manifestations of the human factor, can be interpreted as secondary, derived from the main components of human capital. The education level and culture determine organization and the ability to comply with norms and rules; professional experience and qualifications become the basis for responsibility and risk-taking in decision-making, and intellectual abilities form the basis for creativity and innovation.

The definition of the human factor as a derivative manifestation of human capital allows us to rethink the effectiveness of socio-economic development. In this context, not only the quantitative parameters of human capital accumulation become important, but also the quality of its implementation in the form of specific actions and results. That is, when assessing the human factor and its importance in the development of technologies and the economic system, it is advisable to analyze not only individual behavioral characteristics, but also those social investments that determined their emergence: education, professional training, cultural environment, education system. In such an interpretation, the human factor acts as a key link between the potential resources embedded in human capital and the real productivity of social development.

In addition, the coherence of human capital and the human factor creates the prerequisites not only for achieving performance, but also for the development of innovations and modern digital technologies. After all, as defined Aleknavičiūtė, R. "the main purpose of human capital is to create innovations: to generate new ideas, to create new products, services, or goods, to improve existing products, services, or goods, to establish new business processes and so on" [11, p. 116].

Therefore, in modern conditions, behavioral factors as components of the human factor cannot be considered as self-sufficient or separate manifestations, since they are formed based on human capital and function as its superstructure, which determines their stability and effectiveness. Only in the unity of human capital and the human factor is the true potential of a person and society revealed, since the accumulated knowledge, skills and values have meaning only when they are transformed into specific actions and behavioral manifestations. At the same time, the human factor itself cannot be self-sufficient without a foundation in the form of formed capital. Thus, the effectiveness and success of economic development is determined not by the isolated existence of these categories, but by their harmonious interaction, where capital appears as a foundation, and the factor as its effective reflection in practical activity.

4 PERSON AS THE DRIVING FORCE OF TECHNOLOGICAL CHANGES AND NATIONAL DEVELOPMENT

Throughout history, human has been the main initiator and creator of technological change. In general, no technological variable or innovation arises by itself but is always the result of human reason and imagination, which are primarily aimed at meeting growing needs. The evolution of tools and labour tools from the first stone products to modern digital technologies demonstrates human's constant desire to facilitate physical and mental labour, expand his opportunities for creativity and self-education, as well as increase the level of well-being and quality of life. Accordingly, each new technology arises because of human ingenuity and initiative, the desire to improve living conditions, forming not only a new mechanism for performing actions, but also new ways of thinking, interacting with society and perceiving the world around us.

As Mykola Berdyaev rightly noted, "any tool created by human is directed not only outwardly at the objects of activity, but also inside the subject itself" [9]. It is thanks to the interaction of man and technology that new stages of the evolution of mankind are formed: the transition from the Stone Age to the Iron Age, from agrarian to industrial civilization, from industrial to modern information society. However, we believe that in the outlined process, the key importance belongs to human, since his creativity, initiative and ability to innovate determine the direction and pace of development. Human not only creates equipment and technologies, but also gives them meaning, determines the directions of development and the scale of use. And technologies arise only as tools necessary for the implementation of human ideas, and not as independent drivers of progress. That is, human sets a goal, chooses the path to achieve it and adapts technological solutions to social, cultural and economic needs.

In modern scientific discussion, it is increasingly assumed that the level of human development, which is reflected in the accumulated human capital, directly affects the technological progress of the state and determines its position in global economic competition. Human capital, embodied in knowledge, educational level, professional training, health status and the ability to learn throughout life, forms the basis for the creation and implementation of new technologies. Accordingly, the growth of the educational and intellectual potential of society increases the country's ability to generate innovations, which is reflected in such indicators as the Global Innovation Index, Global Competitiveness Index, Digital Economy and Society Index, Knowledge Economy Index and others.

Based on the analysis of the Global Innovation Index of European countries, we will prove the presence of a direct relationship between the level of human capital development and the innovative capacity of the state. The focus on this index is not accidental, since it comprehensively reflects the ability of the country to create, develop and implement innovations, as well as to effectively use human, intellectual and technological resources. Considering the above considerations, it is advisable to move from theoretical provisions to empirical analysis, which will help to find out to what extent the development of human capital correlates with innovation results and economic growth. We believe that such an approach will allow to identify the systemic impact of the human factor on the state's ability to produce new technologies and integrate them into socio-economic practice. Thus, the main research hypothesis of the analysis is that a higher level of human capital development contributes to an increase in innovative capacity, which, in turn, has a positive effect on the introduction and technologies use, as well as macroeconomic indicators that determine the state of development of the country's economics.

Let us analyze the Global Innovation Index and its components among European countries in 2025 (Fig. 2). The trend of a decrease in all components of the studied index as the transition from highly developed countries to less developed ones is obvious. The highest indicators for all components are observed in Switzerland, Sweden, Great Britain, Finland, the Netherlands and Denmark, which are included in the TOP 10 of this rating. It is these countries that demonstrate a balanced development of the educational and scientific sphere, institutional environment and business infrastructure, which ensures a positive innovation dynamics of development.

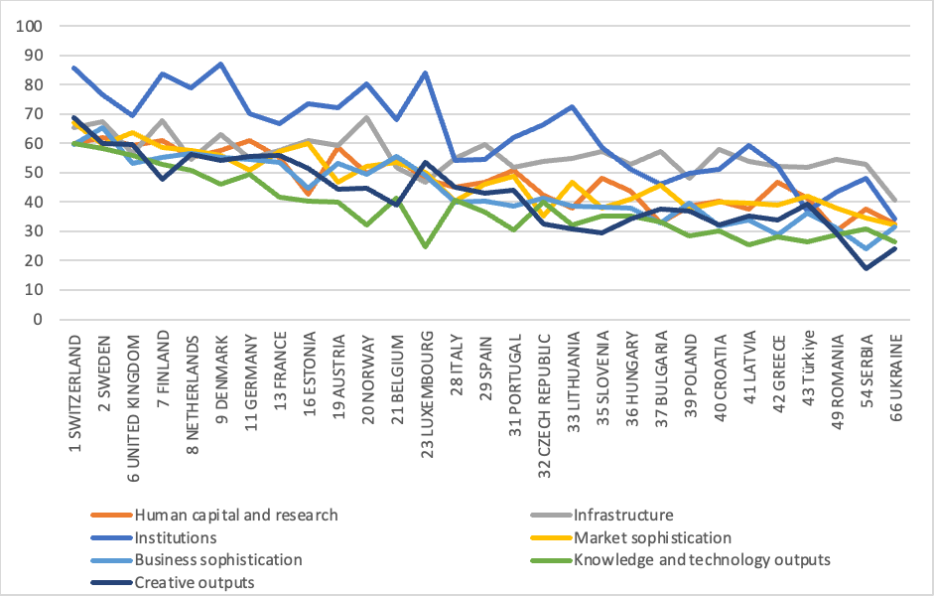


Figure 2: Components of the Global Innovation Index among European countries in 2025 [12].

The countries of Central and Eastern Europe, in particular the Czech Republic, Poland, Hungary, Bulgaria, and Croatia, are characterized by a moderate level of human capital development and relatively lower results. This indicates the presence of potential for innovative growth, which has not yet been fully realized. However, addressing various structural and managerial barriers can become a kind of impetus for activating innovative potential, transforming scientific and educational achievements into real technological products, and increasing the competitiveness of the national economy at the global level. The lowest indicators of European countries are Romania, Serbia, and Ukraine, which reflects both limited resources for scientific research and insufficient integration of the results of educational and scientific activities into the sphere of technological and creative production. However, it is worth noting that over the past four years, Ukraine's position in the studied rating has significantly deteriorated in 2025 it occupies 66th place against 45th in 2020. We believe that the main reason for this decline is the deployment of active military operations on its territory. As a result, a significant part of the country's intellectual potential is used not to ensure technological development, but to meet the needs of the defense-industrial complex.

In addition, the full-scale military aggression in Ukraine further deepened the existing demographic crisis, which has a direct impact on human capital. Thus, according to international experts, the population of Ukraine decreased by approximately 10 million people during the war years [13], which is the total effect of migration, military losses and a decrease in the birth rate. According to UNHCR, as of February 2025, 6.3 million Ukrainians received refugee status in European countries, and about 560 thousand outside Europe [14]. As a result, European countries received additional labor potential in the form of qualified specialists who were trained within the Ukrainian education system, without the need for significant additional investments in their professional training. In contrast, such demographic losses have negative consequences for Ukraine's innovative capacity, including a decrease in the number of young scientists, researchers, and higher education graduates, as well as the loss of potential labor force and part of the creative potential.

Thus, the above graphical analysis allows to state that countries with high investments in education, research and development of human potential occupy leading positions in world innovation rankings, while the deficit of human capital or improper attitude to its formation and development significantly limits the opportunities for economic and technological development.

The Global Innovation Index is an integral indicator consisting of seven main components, each of which reflects a separate aspect of innovation potential and development. To assess the relationship (linear dependence) between the country's place in the overall GII ranking and its values for individual components (sub-indices), we will determine the

Pearson correlation coefficient (r), which is calculated by the (1):

$$r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 (y_i - \bar{y})^2}}. \quad (1)$$

where:

x_i – the value of a separate component of the Global Innovation Index;

y_i – value of the overall rating or integral index;

$\bar{x}$ and $\bar{y}$ – average values of the corresponding indicators.

The resulting Pearson coefficient can vary from – 1 to + 1, which allows us to determine the nature and strength of the relationship, in particular:

1) if r tends to + 1, then there is a strong direct correlation (an increase in the indicator indicates an increase in the rating position). Since a higher place in the rating (a larger number) means a worse result, then such a dependence indicates a negative impact of the indicator on the overall level of innovative development;
2) if r tends to – 1, then there is a strong inverse correlation (an increase in the indicator is accompanied by a decrease in the rating position or the country's promotion to the top positions of the rating). In such a situation, we can say that the indicator has a positive impact on the state's innovative capacity;
3) if r approaches 0, then the relationship is insignificant or absent.

The results of the correlation analysis (Table 1) indicate the presence of stable and mostly strong inverse relationships between the overall rating of the country in the Global Innovation Index and most of its components. That is, the improvement of indicators for individual components of the index (each of which has its own weight) is accompanied by a decrease in the country's ranking, that is, advancement to the top positions in the global innovation space. In addition, the analysis data confirm the previously put forward hypothesis that there is a close relationship between the level of human capital and the innovative capacity of countries. Accordingly, human capital should be defined as a system-forming factor of innovative development. Therefore, promoting the development of human capital is a necessary condition for the growth of innovative potential.

Thus, human capital and the human factor are interconnected components of a single socio-economic mechanism that determines the dynamics of innovative development. Human capital forms an intellectual, creative and value basis for the creation of new knowledge and technologies, and the human factor reflects more behavioral, motivational and cultural aspects of the implementation of this potential in the real economic environment. Based on their interaction, knowledge is transformed into practical innovations, which ensures increased production efficiency, contributes to the growth of key macroeconomic indicators and strengthens the country's competitiveness. Therefore, the development of human capital in combination with the activation of the human factor is a determining condition for technological progress and the sustainability of national development.

Table 1: The relationship between a country's position in the Global Innovation Index and its individual components.

Component of GII	Correlation coefficient – r	Degree of dependence
Institutions	–0,864091574	Very strong correlation. The more effective the institutional, regulatory and business environment, the higher country ranks in innovation rankings.
Human capital and research	–0,88135353	One of the strongest links. Accordingly, human capital is important in shaping innovation capacity.
Infrastructure	–0,674301895	Moderately strong relationship. Infrastructure, including the level of ICT development, is important, but not as important as other components.
Market sophistication	–0,913429169	Very strong dependence. Indeed, countries with a developed financial system and a favourable investment climate occupy higher positions in the ranking.
Business sophistication	–0,929227308	The highest connection. Thus, business innovation, the ability to implement new solutions, and cooperation with the scientific community are key to determining a country's position in the ranking. However, it is worth noting that such elements are mainly determined by the already formed human capital.
Knowledge and technology outputs	–0,85110839	Strong correlation. The more knowledge and technological output a country produces, the more innovative it is.
Creative outputs	–0,911598208	Very strong dependence. Accordingly, the development of the creative industry is an important factor in the overall innovation potential.

5 CONCLUSIONS

Despite the rapid development of technology, which has been especially noticeable in recent decades, it is people who remain the main source of innovation and progress. We agree that modern equipment and machines can work faster and more accurately than people, but they are not able to generate new ideas, produce innovations and improve management decisions. Accordingly, only a person as a carrier of unique human capital can form the basis of scientific and technological evolution and determine the vector of its innovative development, which is confirmed by the results of the correlation analysis. Precisely because the conclusions of the study can be used in a practical sense, in the process of developing national strategies for the development of human capital as a strategic resource of the digital society.

So, in the conditions of digital transformation, the development of technologies and the economic growth of society depends on how effectively human potential is revealed and realized. After all, thanks to the latter, knowledge is transformed into practical results, improvement or creation of new products and technologies, and the formation of competitive advantages. In general, it is advisable to define a person not only as a determinant of economic growth, but also as an intellectual basis for civilizational progress, capable of initiating changes and at the same time ensuring the harmonization of technological and social development. We believe that further scientific research within this area should be aimed at developing an effective mechanism not only for managing the development of human capital, but also for its implementation in various sectors of the national economy.

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Readiness for the Economy of the Future: Digitalization, AI, Innovation, Sustainability

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Keywords: Economy of the Future, Digitalization, Artificial Intelligence, Innovation, Human Capital, Sustainable Development, Ukraine, Germany.

Abstract: The article examines the level of readiness of countries for the economy of the future based on an integral indicator formed from four international indices: Government AI Readiness Index (assessment of the role of artificial intelligence), Network Readiness Index (digitization and network effects), Global Innovation Index (innovation and human capital) and SDG Index (sustainable development). A methodology for constructing an integral indicator Future Economy Readiness Level (FERL) has been developed, which allows combining digital, innovative and socio-economic dimensions of development into a single generalized assessment. A comparative analysis of Ukraine and Germany in 2020–2024 was conducted, and FERL was also forecasted for 2025, which made it possible to identify the dynamics of key indicators and determine the strengths and weaknesses of both countries in the context of readiness for the economy of the future. The results of the study can be used to form strategies for digital transformation, innovation policy and ensuring sustainable development.

1 INTRODUCTION

Modern global transformations in digital technologies, innovations, and sustainable development require a rethinking of states' economic strategies. The concept of the economy of the future denotes a stage of development based on digitalization, AI integration, innovative production and management, and sustainability principles. However, countries' readiness for these changes varies and requires comprehensive assessment.

International indices are used to evaluate states' positions in this transition, including: Government AI Readiness Index (AI implementation readiness), Network Readiness Index (digitalization and network effects), Global Innovation Index (innovation potential and human capital), and SDG Index (progress on Sustainable Development Goals). While each index reflects a specific aspect, their combined use provides a holistic view of a country's readiness.

The article aims to develop an integrated approach to assessing countries' readiness for the economy of the future using these indices and to compare Ukraine and Germany, identifying strengths, weaknesses, and practical recommendations for enhancing global competitiveness.

2 RELATED WORKS

A significant number of scholars are investigating various aspects of the transition to the economy of the

future. In [1], the Oxford Insights Government AI Readiness Index, its methodology, and challenges of use are analyzed. The author suggests ways to overcome the problems of data availability in developing countries. In [2], the study uses the DEA (Data Envelopment Analysis) method to assess the digital development of countries, based on the Network Readiness Index indicators. The authors propose an alternative approach to ranking countries and show that different methods can significantly change a country's place in the rankings. In [3], the results of the Network Readiness Index 2020 are analyzed in the context of COVID-19. The author emphasizes that the pandemic has accelerated digital transformation and highlighted inequalities between countries in readiness for the digital economy. In [4], the impact of human capital on the Global Innovation Index is analyzed, concluding that countries with a high level of education and qualification of the population show better innovation results. In [5], the role of innovation and human capital in shaping the knowledge economy is analyzed. It is shown that innovation directly depends on the level of development of human potential and the education system. The article [6] examines the intellectual potential of Ukrainian regions (educational, scientific, and innovative) in wartime conditions, conducts fractal analysis and forecasts key indicators. Negative trends are identified and the need to strengthen human capital and innovative capabilities for economic recovery is emphasized. In [7], a study was conducted on the relationship between digitalization, corporate governance, and reporting on the Sustainable Development Goals (SDGs). The author argues that digitalization can increase the transparency and effectiveness of sustainable development. In [8], the Digital Economy and Society Index (DESI) is studied to determine the impact of the Digital Economy and Society Index (DESI) on sustainable development indicators in the EU. The results show that countries with a higher level of digital economy have better results in the field of environmental and social sustainability. In [9], the digital transformation is studied to determine the impact of social sustainability in EU countries. The authors argue that digitalization has a positive but uneven impact on achieving the SDGs. The paper [10] examines the role of AI and aerospace engineering in achieving the Sustainable Development Goals. The article criticizes existing approaches and proposes interdisciplinary solutions. This study assumes a comprehensive consideration of the considered directions to ensure the transition to the economy of the future.

3 METHODOLOGY

The economy of the future is an integrated model of socio-economic development that combines digital transformation, the implementation of artificial intelligence technologies, a high level of innovation, the development of human capital and adherence to the principles of sustainable development. It is based on interconnected subsystems - digital, technological, innovative and socio-ecological - that shape the state's ability to adapt to global challenges, ensure economic sustainability, competitiveness and long-term growth.

Within this concept, the economy of the future is viewed not as a universal model, but as a complex, multi-level state of maturity of a country, reflecting its readiness to effectively use digital tools, data, artificial intelligence, innovative solutions, as well as to implement a policy of sustainable development and inclusive growth.

The proposed four subsystems are logical and methodologically sound, as they cover all key dimensions of modern socio-economic development. The digital subsystem reflects the level of digitalization of processes, access to digital infrastructure, use of data and digital services. This is the basic level of transformation, without which innovation and automation are impossible. The technological subsystem (including AI) covers the development of technologies, automation, artificial intelligence, R&D. It ensures increased productivity and competitiveness, acting as the core of technological change. The innovative and educational subsystem (human capital) takes into account the quality of education, skills, the ability to innovate, and the development of human potential. It is critical for adapting to technological change, training personnel and building the capacity for innovation. The socio-ecological subsystem (sustainable development) covers the environmental, social and institutional aspects of sustainable development. Ensures balance of transformations and takes into account social risks, inclusion and environmental responsibility. Thus, the choice of these four subsystems ensures completeness, systematicity and balance of the assessment, since each of them covers a separate dimension of development, and together they form a holistic model.

For a comprehensive assessment of a country's readiness for the economy of the future, an integrated indicator has been proposed - the Future Economy Readiness Level (FERL). It is based on the following components and their corresponding internationally recognized indices (Fig. 1, Table 1).

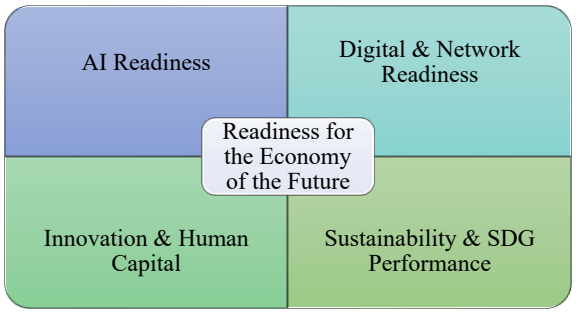


Figure 1: Structural elements of a country's readiness for the economy of the future.

Table 1: Structural elements of the economy of the future.

Structural component	Characteristic	Selected indicator
AI Readiness	determines the role of AI in economic development and the state's ability to introduce innovative technologies	Government AI Readiness Index (GARI)
Digital & Network Readiness	takes into account digitalization, infrastructure availability and network effects	Network Readiness Index (NRI)
Innovation & Human Capital	reflects the innovative potential and quality of human capital	Global Innovation Index (GII)
Sustainability & SDG Performance	demonstrates sustainable economic, social and environmental development	SDG Index

FERL calculation stages:

Stage 1. Data collection - obtaining official values of the specified indices for selected countries (Ukraine and Germany) in the period 2020-2024.

Stage 2. Normalization of indicators. Since all indices have a scale from 0 to 100, their values were used without additional transformations. If necessary, they are brought to a single scale.

Stage 3. Determination of weight coefficients. For a system with a descending order of priorities among N alternatives, weighting factors were determined using the Fishburne method:

$$p_i=(2(N-i+1))/((N+1)N),\ i=1..N. \quad (1)$$

Stage 4. Calculation of the integral indicator:

$$FERL=w_{GARI}\cdot GARI+w_{NRI}\cdot NRI+w_{GII}\cdot GII+w_{SDG}\cdot SDG. \quad (2)$$

Stage 5. Comparison of results - FERL integral values are analyzed in dynamics and compared between countries.

Interpretation of results:

- Low level (0-20 points);
- Below average level (21-40 points);
- Average level – (41-60 points);
- Above average level – (61-80) points;
- High level – (81-100 points).

Thus, the integral FERL indicator allows combining various aspects of digitalization, innovation and sustainable development into a single generalizing assessment, which provides the possibility of interstate comparisons and the formation of strategic conclusions.

4 RESULT AND DISCUSSION

The study involves a comparative analysis of Ukraine and Germany as examples of countries with different levels of economic and technological development. This approach allows us to assess the universality of the integral indicator and demonstrate its applicability both for countries undergoing transformation and integration into world markets, and for highly developed economies that are already shaping global trends in digitalization, innovation, and sustainable development. This provides an opportunity to identify differences in development strategies, strengths and weaknesses of each country, and also forms the basis for developing practical recommendations.

4.1 AI Readiness

The development of AI is one of the key factors of the economy of the future. The Government AI Readiness Index (GARI) measures the level of readiness of government institutions, regulatory environment and digital infrastructure to implement AI technologies, which directly affects the competitiveness of the country. Table 2 and Figure 2 show a comparison of the values of this index for Ukraine and Germany over time.

Based on GARI data, the following conclusions can be drawn. Germany is consistently among the leaders in terms of AI readiness, ranking in the top 15, with a GARI in the range of 72,64-78,97. Ukraine is showing a gradual increase in readiness: its ranking improved from 57th place in 2020 to 54th in 2024, and the GARI index increased from 48,90 to 60,57. Despite the positive dynamics, Ukraine’s readiness

level is still significantly lower than Germany, which indicates the need for further development of digital and innovation competencies for accelerated AI implementation.

Table 2: GARI for Ukraine and Germany [11].

Year	Indicator	Germany	Ukraine
2020	Rank	4/172	57/172
	GARI	78,97	48,90
2021	Rank	8/160	64/160
	GARI	77,26	50,58
2022	Rank	15/181	60/181
	GARI	72,64	52,80
2023	Rank	8/193	60/193
	GARI	75,26	53,29
2024	Rank	8/188	54/188
	GARI	76,90	60,57

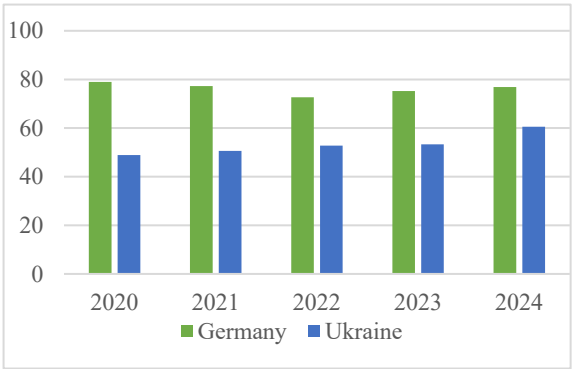


Figure 2: Comparison of GARI values for Ukraine and Germany in dynamics.

Table 3 shows the values of the index components for the countries studied, and Figure 3 details their values in 2024.

Table 3: The values of the index components for Ukraine and Germany [11].

Year	Country	Government	Technology Sector	Data and Infrastructure
2020	Germany	78,22	68,09	90,61
	Ukraine	-	-	-
2021	Germany	78,04	67,68	86,07
	Ukraine	52,36	38,19	61,19
2022	Germany	75,22	60,42	82,29
	Ukraine	68,96	34,68	54,74
2023	Germany	80,78	63,28	81,72
	Ukraine	68,93	36,18	54,75
2024	Germany	79,24	64,91	86,55
	Ukraine	73,42	41,93	66,37

Thus, Germany shows consistently high scores in all three components (government, technology sector, data and infrastructure), indicating comprehensive readiness for AI implementation. Ukraine shows gradual improvement, especially in the area of governance (from 52,36 in 2021 to 73,42 in 2024), while the technology sector and infrastructure remain relatively weak, limiting overall readiness.

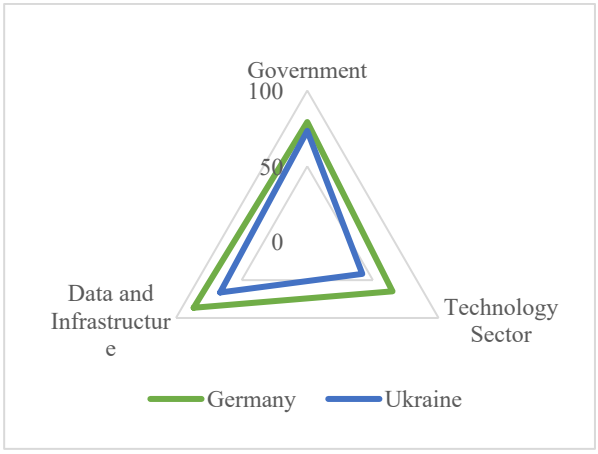


Figure 3: Comparison of the level of GARI components for Ukraine and Germany in 2024.

4.2 Digital and Network Readiness

The Network Readiness Index (NRI) reflects the level of digitalization of the economy, the development of information and communication technologies, the efficiency of digital networks, and the readiness of society to use digital innovations. This indicator determines the ability of a country to integrate into the global digital space. Table 4 and Figure 4 show a comparison of the values of this index for Ukraine and Germany over time.

Table 4: NRI for Ukraine and Germany [12].

Year	Indicator	Germany	Ukraine
2020	Rank	9 / 134	64 / 134
	NRI	77,48	49,43
2021	Rank	8 / 130	53 / 130
	NRI	78,95	55,70
2022	Rank	8 / 131	50 / 131
	NRI	76,11	55,71
2023	Rank	9 / 134	43 / 134
	NRI	74,00	55,16
2024	Rank	9 / 133	43 / 133
	NRI	73,54	55,32

Based on NRI data, the following conclusions can be drawn. Germany consistently maintains high

positions in the ranking (8-9th place) with an NRI of over 73, which indicates a strong digital infrastructure and readiness for network transformations. Ukraine demonstrates a gradual stabilization of NRI indicators at the level of 55-56, while improving its position in the ranking from 64th place in 2020 to 43rd in 2024. Overall, Ukraine is progressing, but remains significantly behind Germany in the area of digital readiness and network capabilities.

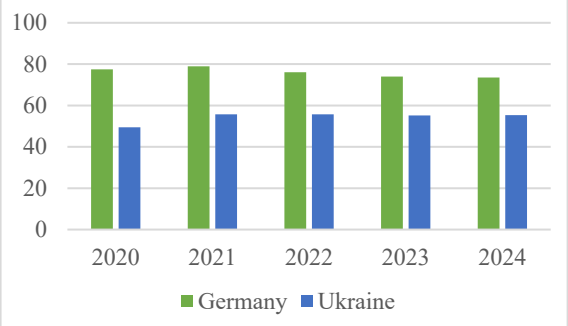


Figure 4: Comparison of NRI values for Ukraine and Germany in dynamics.

Table 5 and Figure 5 show the values of the index components for the studied countries in 2024.

Table 5: Comparison of the level of NRI components for Ukraine and Germany in 2024 [12].

Country	Показн	Technology	People	Governance	Impact
Ukraine	Rank	44	28	56	51
	Score	48,96	51,83	63,14	57,34
Germany	Rank	4	8	16	9
	Score	72,54	63,77	82,52	75,35

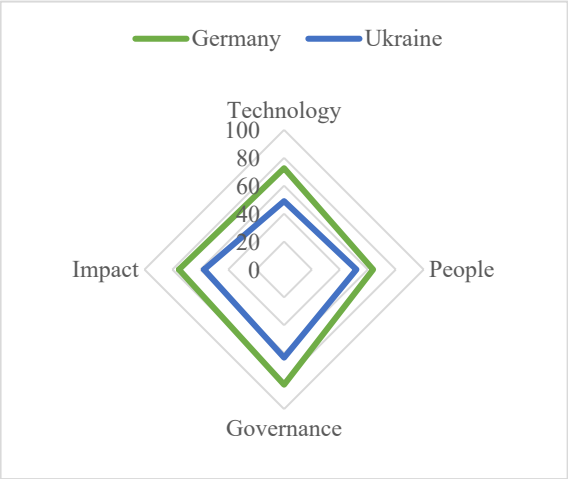


Figure 5: Comparison of the level of NRI components for Ukraine and Germany in 2024.

In 2024, according to the NRI, Germany ranks 9th with a score of 73,54, demonstrating a consistently high level of digital readiness and developed network infrastructure. Ukraine ranks 43rd with an NRI of 55,32, indicating a moderate level of digital readiness and the need for further development of infrastructure and technologies.

4.3 Innovation and Human Capital

The Global Innovation Index (GII) assesses technological capability, human capital development, research activity, innovation infrastructure and innovation performance. It is the combination of innovation and human capital that creates the foundation for sustainable economic growth in the long term. Table 6 and Figure 6 show a comparison of the values of this index for Ukraine and Germany over time.

Table 6: GII for Ukraine and Germany [13].

Year	Indicator	Germany	Ukraine
2020	Rank	9	45
	GII	56,55	36,32
2021	Rank	10	49
	GII	57,3	35,6
2022	Rank	8	57
	GII	57,2	31,0
2023	Rank	8	55
	GII	58,8	32,8
2024	Rank	9	60
	GII	58,1	29,5

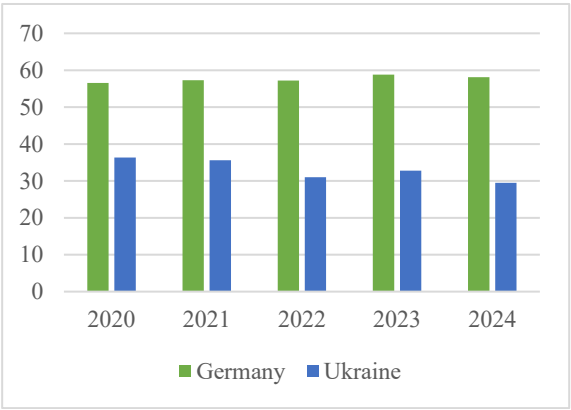


Figure 6: Comparison of GII values for Ukraine and Germany in dynamics.

According to the GII 2020-2024, Germany consistently maintains high positions (8-10th place) with GII scores of 56–59, indicating strong innovation potential. Ukraine shows a deterioration in its ranking from 45th place in 2020 to 60th in 2024

and a decrease in GII from 36,32 to 29,5, indicating a weak development of the innovation environment and the need for active reforms.

Table 7 and Figure 7 show the values of the index components for the studied countries in 2024.

Table 7: Comparison of the level of GII components for Ukraine and Germany in 2024 [13].

Structural elements	Germany	Ukraine
GII	58,1	29,5
Institutions	73,5	30,8
Human capital and research	61,4	34,3
Infrastructure	52,9	35,5
Market sophistication	56,4	25,7
Business sophistication	55,3	31,8
Knowledge and technology outputs	53,9	31,1
Creative outputs	58,6	23,7



Figure 7: Comparison of the level of GII components for Ukraine and Germany in 2024.

Germany scores highly in all GII structural elements, especially in the areas of institutions (73,5), human capital and research (61,4) and creative output (58,6), indicating a strong innovation potential and a developed innovation environment. Ukraine scores significantly lower in all components, especially in market complexity (25,7) and creative output (23,7), indicating a weak development of innovation potential and the need to improve institutions, infrastructure and human capital.

4.4 Sustainability and SDG Performance

The SDG Index (SDGI) reflects a country's progress in achieving the UN Sustainable Development Goals. This index characterizes the environmental, social and economic balance that serves as the foundation for long-term sustainability and shaping the economy of the future. Table 8 and Figure 8 show a comparison of the values of this index for Ukraine and Germany over time.

Table 8: SDG Index for Ukraine and Germany [14].

Year	Indicator	Germany	Ukraine
2020	Rank	5/166	47/166
	SDGI	80,8	74,2
2021	Rank	4/165	36/165
	SDGI	82,5	75,5
2022	Rank	6/163	37/163
	SDGI	82,2	75,7
2023	Rank	4/166	38/166
	SDGI	83,4	76,5
2024	Rank	4/167	44/167
	SDGI	83,4	74,8
2025	Rank	4/167	42/167
	SDGI	83,7	75,7

Germany consistently maintains high positions (4-6th place) with SDGI indicators above 80, demonstrating effective achievement of the Sustainable Development Goals. Ukraine fluctuates between 36 and 47th place, with SDGI 74-76, indicating gradual progress, but still significantly lagging behind the leaders in the field of sustainable development.

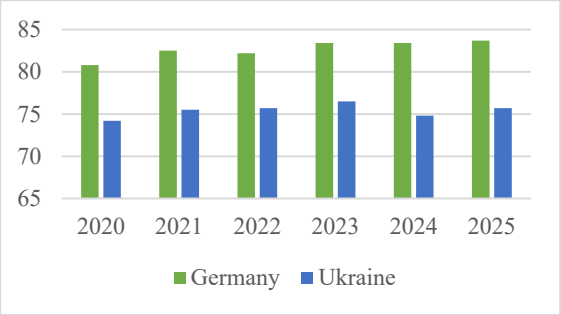


Figure 8: Comparison of SDG Index values for Ukraine and Germany in dynamics.

Figures 9 and 10 show the average performance by SDG for Germany and Ukraine, respectively.

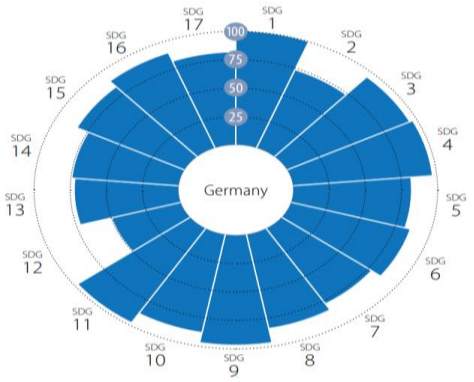


Figure 9: Average performance by SDG for Germany [14].

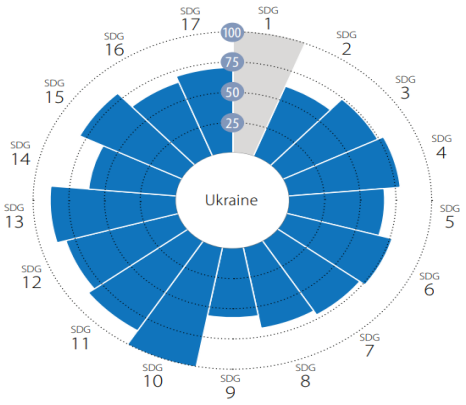


Figure 10: Average performance by SDG for Ukraine [14].

In 2024, in terms of average effectiveness of implementing the Sustainable Development Goals, Germany demonstrates high performance in all areas, while Ukraine lags significantly behind, especially in Goals 2, 9, 14, 16, 17.

4.5 Calculation and forecasting FERL

According to the Fishburne method, AI Readiness received the highest (rank 1), since the development of artificial intelligence, automation and high technologies determines the speed and direction of structural changes in the economy of the future, forming its core of transformations. Digital & Network Readiness took second place (rank 2), because it acts as a critical infrastructure foundation for the implementation of technologies, providing access to data, network interaction and platform models, although it does not directly drive transformations. Innovation & Human Capital (rank 3) ensures the development of human capital and innovative activity, which allows adapting and scaling technological changes, but its impact manifests itself gradually and depends on technological and digital capabilities. Sustainability & SDG Performance (rank 4) forms long-term stability and balance of transformations through the principles of sustainable development, but its effect is indirect and is not the primary driver of the economy of the future.

Therefore, according to the proposed ranks and according to (1), the following weighting coefficients were obtained:

- w_{GARI}=0,4;
- w_{NRI}=0,3;
- w_{GII}=0,2;
- w_{SDG}=0,1.

Table 9 shows the values of the studied indices and the calculated indicator.FERL.

Table 9: Estimated value of the indicator FERL.

Year	Country	GARI	NRI	GII	SDGI	FERL
2020	Germany	78,97	77,48	56,55	80,8	74,22
	Ukraine	48,9	49,43	36,32	74,2	49,07
2021	Germany	77,26	78,95	57,3	82,5	74,30
	Ukraine	50,58	55,7	35,6	75,5	51,61
2022	Germany	72,64	76,11	57,2	82,2	71,55
	Ukraine	52,8	55,71	31	75,7	51,60
2023	Germany	75,26	74	58,8	83,4	72,40
	Ukraine	53,29	55,16	32,8	76,5	52,07
2024	Germany	76,9	73,54	58,1	83,4	72,78
	Ukraine	60,57	55,32	29,5	74,8	54,20
2025	Germany	84,03	72,17	58,4	83,7	75,31
	Ukraine	61,30	57,12	28,8	75,7	54,99

To predict values for 2025, the following models were used according to the high value of the coefficient of determination (Table 10).

Figure 11 shows a comparison of the FERL indicator for Ukraine and Germany.

According to the FERL 2020–2025, Germany demonstrates consistently high FERL values (71–75), indicating a strong and balanced readiness for the economy of the future in all components (AI,

digitalization, innovation, sustainable development). Ukraine shows a gradual increase in FERL from 49,07 in 2020 to 54,99 in 2025, but remains significantly behind Germany, especially due to low innovation indicators (GII).

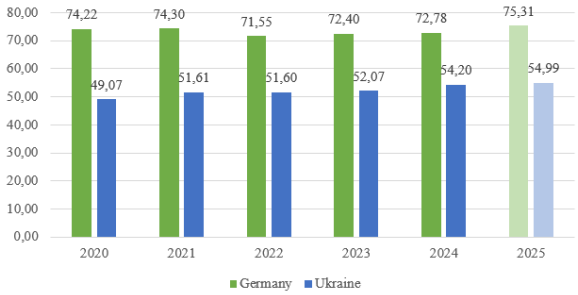


Figure 11: A comparison of the FERL indicator for Ukraine and Germany.

Table 10: Selected models for forecasting index values for 2025.

Index	Germany	Ukraine
GARI	$y = 0,1605x^3 - 0,4482x^2 - 2,8047x + 82,329$	$y = 45,962e^{0,048x}$
NRI	$y = -1,283x + 79,865$	$y = 3,4204\ln(x) + 50,989$
GII	$y = -0,0857x^2 + 0,9743x + 55,61$	$y = 0,0886x^2 - 2,1754x + 38,596$

Figure 12 shows a breakdown of the constituent elements (indices) and the FERL indicator in 2025.

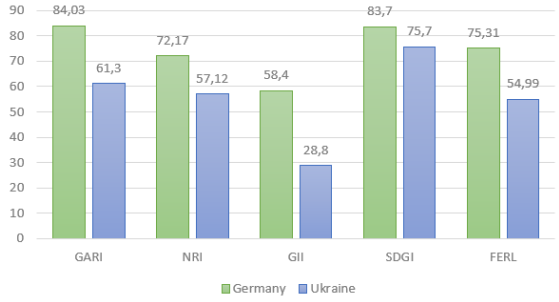


Figure 12: A breakdown of the constituent elements (indices) and the FERL indicator in 2025.

So, for Germany, the FERL level is above average, for Ukraine - at an average level. The lowest level in the structure of components for both countries is the GII. The highest value is in the SDG Index. Overall, Ukraine is progressing, but needs active development of digital, innovation and institutional components for an accelerated transition to the economy of the future.

5 CONCLUSIONS

The article proposes a methodology for assessing the readiness of countries for the economy of the future based on an integral indicator formed from four key indices. The Government AI Readiness Index reflects the role of artificial intelligence in the future economy, the Network Readiness Index characterizes the level of digitalization and the use of network effects, the Global Innovation Index determines the innovative potential and quality of human capital, and the SDG Index assesses the sustainability of development as a basis for long-term growth. It is predicted that in 2025, Ukraine's readiness level will be 54,99 points (average level), while for Germany – 75,31 points (above average). The lowest values for both countries are recorded for the Global Innovation Index, and the highest - for the SDG Index, which confirms the leading role of sustainable development in shaping the economy of the future. To increase the level of readiness, Ukraine should focus on developing an innovative environment, investing in human capital, building digital infrastructure, and more actively implementing solutions based on artificial intelligence.

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Digital Technologies for Attracting the Labor Force to Industry in Ukraine

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Keywords: Digital Technologies, Labor Force, Industrial Enterprises, Expansion of Labor Potential, Intellectualization of Labor.

Abstract: The article considers the problem of attracting labor resources to Ukrainian industry in the conditions of demographic decline, migration losses and large-scale war. The relevance of the study lies in the urgent need to overcome the labor force shortage and ensure sustainable development of industry through the use of digital technologies. The purpose of the study is to analyze the potential of modern digital tools in forming an effective system of attracting, selecting, motivating and retaining personnel at industrial enterprises. The methodological basis is the structural-functional and systemic approaches, which allowed building a conceptual system of providing labor force with the use of digital tools, such as national employment platforms, artificial intelligence algorithms, candidate management systems, chatbots, mobile applications, e-learning systems and predictive analytics. It is assumed that the use of digital technologies will significantly reduce the time and costs of personnel selection, increase the efficiency of HR processes, and also contribute to the growth of employee competencies through continuous training and professional development. At the same time, international integration mechanisms, in particular electronic visa services and migration platforms, open up access to foreign labor resources and accelerate the adaptation of labor migrants. The theoretical contribution of the study lies in the proposed conceptual system for attracting labor force to industrial enterprises using digital technologies, which is presented as a multi-level architecture of socio-technical innovations, connecting state institutions, enterprises and employees into a single digital system. The practical significance of the results is reflected in providing industrial enterprises with a roadmap for the implementation of digital tools in personnel management, which ensures sustainable growth even in wartime conditions.

1 INTRODUCTION

Digital transformation is becoming a key driver of economic growth, labor force development, and public administration efficiency. Using various digital innovation platforms, regulatory mechanisms, and strategic partnerships, the country is ensuring the development of relevant competencies as a key asset of its labor force.

Ukraine is currently experiencing a severe brain drain, labor force reduction, and the largest demographic crisis. Since the beginning of the war, a significant part of the Ukrainian labor force has emigrated or changed its place of residence, becoming victims of military violence. This difficult labor situation will continue to affect business operations throughout Ukraine and threaten its future recovery. A survey conducted by the Ukrainian Institute for Economic Research and Policy Consulting in October 2024 showed [1] that labor shortages are the biggest concern for the private sector: more than 60% of surveyed companies are experiencing difficulties in hiring qualified employees. At the same time, according to the latest estimates, the current unemployment rate in Ukraine at the end of 2024 was 12.7%. This means that unemployment coexists with a labor shortage. Even before the war, Ukraine voiced a difficult

demographic situation: low fertility rates, premature mortality among men, and emigration of young Ukrainians in search of better economic opportunities abroad. According to estimates by the International Labor Organization, by 2032 Ukraine will lack 8.6 million workers (compared to 2022). And now the Government of Ukraine, in cooperation with the international community and relevant stakeholders, should develop and implement a comprehensive human capital development strategy to meet current and future labor needs. This will require a combination of short-term and long-term measures aimed at expanding the country's labor potential. However, the current labor problems in Ukraine are part of a broader demographic problem. The country has the lowest fertility rate in Europe, with less than one child per woman, compared to an average of 1.3–1.8 children per woman in Eastern Europe. In addition, Ukraine currently has a high rate of premature mortality, especially among men, and it is not just the country's traditional problems of alcoholism, accidents, but other current trends such as emigration, general ill health, and rapid aging that are complicating the country's demographic landscape. The last census of Ukraine, conducted in 2001, recorded a population of 48.5 million. The war caused many Ukrainians to emigrate abroad, with an estimated 20,000 Ukrainian children forcibly deported to Russia, and thousands more living under temporary occupation. Sadly, many Ukrainians died during the war. As of December 2024, the President of Ukraine reported that 43,000 Ukrainian military personnel had been killed. In addition, about 12,000 civilians had been killed, and thousands more Ukrainians had been injured or disabled. According to the Office of the United Nations High Commissioner for Refugees, as of November 2024, there were about 4 million internally displaced persons in Ukraine. Another 6.8 million refugees were registered in other countries, and approximately 14.6 million people were in need of humanitarian assistance. As a result of these trends, the population of Ukraine had decreased to 35.8 million as of July 2024 - or to 31.1 million if only the territories under the control of the Ukrainian government were taken into account. If this situation is not changed, the population of Ukraine could subsequently decrease to 28.9 million by 2041 and to 25.2 million by 2051, according to the National Academy of Sciences of Ukraine [1].

The population decline and the shrinking labor force will be a major shock to Ukraine's economy, and the negative effects will be felt for many years to come. Empirical research shows that time spent out of work can not only lead to skill depreciation, but also affect national productivity and wages. A protracted war will have even more serious consequences for Ukraine's education, and this will directly affect the country's future human capital. Schooling has been and continues to be interrupted by the hostilities. Students have suffered significant educational losses. According to previous research by the Organization for Economic Cooperation and Development, the war in Ukraine will lead to a 7% reduction in the overall national productivity factor by 2035 [1]. In addition, poor mental health affects individuals and has a ripple effect on society and the economy. Even before the outbreak of the large-scale war, an estimated 30% of Ukraine's population had a mental disorder at some point in their lives. During the first year of the Russian invasion, approximately 26% of Ukrainians met the diagnostic criteria for post-traumatic stress disorder alone.

All of the above factors lead to missed working days, reduced labor productivity, quality and efficiency of labor potential use, and necessitate the involvement of innovative digital technologies in the process of providing labor to industry in Ukraine.

2 ANALYSIS OF LATEST RESEARCH AND PUBLICATIONS

The issues of digitalization of labor processes and labor force involvement in industrial enterprises have received wide coverage in the works of both domestic and foreign researchers.

Thus, Nemchenko T.A. and Divizyniuk B.M. [2] consider the transformation of labor under the influence of digitalization, and Androsova O. [3] analyzes digital tools used at Ukrainian enterprises. Research by the Razumkov Center [4] and Rumyantsev A., Kovbuch T. [5] identify global risks and the need for retraining of the labor force. Shatalova L. [6] focuses on digital competencies, while in previous publication Kalinesku T., Likhonosova G., Zelenko O. [7] emphasize the importance of integrating innovations into business processes. The works of Maksymenko I., Akimova A., Markova S. [8] and Dziubenko O., Galaz L., Baly O. [9] highlight the impact of war on digital transformation. At the same time, Azmuk N., Grishnova O., Kuklin O. [10] explore the global digital labor market. Cepeda-Cardona J., Arias-Pérez J. [11] reveal the risks of "technostress", and Markaryan M., Bilyi D., Yuldashev S. [12]

emphasize the importance of legal aspects of the digital transformation of the economy.

In general, the analysis of the literature demonstrates several key contradictions and gaps in the scientific discourse. First, digitalization is most often viewed as either a technical upgrade of enterprises or a change in employee competencies, but there are almost no approaches that synthesize these levels into a single system of digital human resources. Second, research rarely takes into account the specifics of the industrial sector, which differs significantly from IT or service industries in terms of the nature of competencies, personnel development strategies, and social risks. Third, modern publications pay insufficient attention to the integration of analytical tools - from systems for forecasting personnel needs to indicators of intellectualization of labor potential - although it is precisely such systems that determine the effectiveness of digital transformation in industry.

Thus, scientific publications outline the general trends in the digital transformation of labor, but do not form a holistic concept of attracting labor resources to industry based on digital technologies. This gap necessitates the development of an integrated approach that combines digital recruitment tools, HR process automation, competency development systems, analytical forecasting methods, and mechanisms for international personnel mobility.

3 RESEARCH METHODOLOGY

The methodological basis of the study is a systemic, structural-functional approach and a comparative-analytical method, which allowed to characterize comprehensively the impact of digital technologies on the processes of attracting labor force to industrial enterprises in Ukraine. The systemic approach provided the study of digitalization as a multi-level interaction of technological, organizational and social factors, while the structural-functional approach made it possible to identify the key elements of digital staffing - recruitment, automation of HR procedures, training, motivation and labor market analytics - and determine their role in the formation of modern labor potential. The comparative-analytical method was used to compare Ukrainian practices of digital recruitment and personnel development with international approaches, which allowed to outline the directions of adapting global solutions to the conditions of war and demographic decline. Methods of analysis, synthesis and logical generalization were used to form the author's conceptual system for attracting labor force to industrial enterprises in Ukraine based on digital technologies that integrates various digital solutions into a holistic model of enterprise HR work.

The study also applied content analysis of analytical reports, statistical data and reviews of business practices, which allowed identifying key trends: workforce shortage, changing structure of demand for competencies, increasing role of HR process automation and use of artificial intelligence in recruiting.

4 MAIN RESEARCH RESULTS

Digital technologies, based on the implementation of advanced information and communication tools in all spheres of economic life [7], not only lead to an increase in the efficiency of production and commercial processes, but also create numerous challenges to the functioning of traditional economic mechanisms, transforming traditional business models, changing the nature of labor activity and creating the need to adapt labor potential to new working conditions. It is digitalization that creates new economic requirements for providing labor, where the formation of intellectual, creative, and innovative capital, which is based on the creation of the latest digital platforms and the use of innovations, is decisive. It is also necessary to emphasize that strengthening the role of information resources is becoming a fundamental criterion for ensuring the competitiveness of individual industrial enterprises, organizations and the country as a whole.

At the same time, the digital environment stimulates the development of innovations, which in turn lead to substantive shifts in the functioning of the labor market, affecting the organization of labor processes, labor supply, employment structure and the nature of labor activity. The key factors that influence the labor force supply of industrial enterprises in Ukraine are presented in Table 1.

In addition to the requirements for the modern labor force involved in industry, it is also necessary to talk about digital technologies that are traditionally used for its recruitment, namely [2, 3]:

Table 1: Key factors influencing labor force supply [2].

Key factors	The nature of the impact
Automation and digitalization of work processes	Transition from manual to routine work, using automated systems and algorithms, artificial intelligence, for big data analysis, forecasting and decision-making, integration of digital platforms for business process management
Changing professional competencies and qualification requirements	Growing demand for highly qualified specialists with digital skills, analytical and creative thinking, and the ability to work with large databases and artificial intelligence
Work flexibility and personalization	Transition to the use of digital technologies to individualize work tasks and increase worker mobility
Intellectualization of labor	Strengthening the role of cognitive processes and strategic thinking, the use of neural networks in performing professional tasks, and the analysis and adoption of management decisions
New forms of labor interaction	Using digital switching platforms for robot coordination, interactive collaboration, and working in virtual teams

1) Social networks and specialized platforms that allow companies to post vacancies and find candidates, as well as use advertising to attract the necessary specialists.
2) Candidate management systems that allow you to automate the hiring process, from the stage of submitting resumes and interviews to making a hiring decision and help process a large number of applications, sort them by key criteria, and track candidates during the hiring process.
3) Video interview software that allows you to interview candidates who are in different locations, which significantly saves time and resources.
4) Chatbots and artificial intelligence (AI), used to automate initial contact with candidates, answer questions, and collect basic information. AI can analyze large amounts of data to help identify the best candidates and predict their job performance. However, the current level of AI adoption among Ukrainian companies remains low (38.2%) [3], although future plans indicate a high level of readiness for its use (91%) by industrial enterprises. Overall, AI adoption in Ukrainian industrial enterprises is at an early stage, as the majority of existing enterprises (45.9%) believe that AI has the potential to increase productivity, and 43.3% expect AI to improve innovative products [3].
5) Mobile applications used to simplify the process of applying for jobs, receiving notifications about new vacancies, and communicating with recruiting firms.

In general, it is planned to create 344 million jobs in the international labor market (which includes Ukraine) by 2030 through the use of digital technologies, including 190 million jobs to solve the current problem of unemployment [4, p. 72]. Moreover, global GDP may grow by $9 trillion due to the automation of jobs using AI technologies. 375 million workers (about 14% of the global labor force) will be forced to change their profession. Therefore, enterprises that have to adapt to new digital technologies in the 21st century should take into account the following trends in the world, which are characterized by [5]:

1) Industrialization technologies. As a rule, most of these technologies are introduced in industries where new computer communication technologies and various means of electronics are widely used, which allows to increase the efficiency and capacity of production, labor productivity and create conditions that force workers to use these technologies, which are becoming more accessible due to the development of digital technologies.
2) Globalization processes that allow the majority of the working population of different countries of the world to establish certain information connections, which allows to interconnect the flows of money, goods, services and ensure their growth.
3) Competition. Globalization processes and digital technologies force enterprises to compete not only in the domestic market, but also for a share of the world market, which can be obtained on the basis of the rapid application of technological innovations.
4) Continuous and rapid changes in social life. Therefore, each enterprise must build its production mobile and flexible, so that it can quickly adjust to changing development conditions. Today's changes occurring in the environment cannot be resolved on the basis of past experience and traditions. Therefore, modern enterprises must learn new unprecedented ways to solve problems.
5) The technological speed of changes in business, which must correspond to the speed of the life

cycle, which is associated with the intensification of competition under the influence of the application of technological innovations.

6) The complexity of production, which is becoming an everyday norm and is associated with new opportunities, innovations and improvisation in solving emerging management problems.

The above characteristics of the use of digital technologies show certain changes that are taking place at industrial enterprises within the framework of providing jobs with labor resources. The main task of every modern industrial enterprise in Ukraine is not so much the filling of all workplaces with the necessary qualified labor force, but rather the readiness of all employees of enterprises for complex training based on digital and information technologies, innovative management and flexible methods of restructuring production processes to meet the requirements of the time. Enterprises seeking successful digital transformation must not only possess digital assets but also develop or acquire among their employees the competencies required for working with digital technologies [13]. According to recent studies across OECD countries, Finland, Norway, Sweden, and New Zealand demonstrate the highest levels of readiness for digital transformation, while Slovakia, Poland, and Greece show the lowest levels of readiness [14].

According to the results of the analysis, it is possible to formulate a conceptual system for attracting labor to the industry of Ukraine using digital technologies (Table 2).

The presented conceptual system for attracting labor to industrial enterprises of Ukraine based on digital technologies is imagined as a holistic, multi-level architecture of socio-technical innovation, which combines digital infrastructure for personnel search and selection, automation of HR processes, tools for motivation and professional development of employees, labor market analytics, and mechanisms for international integration of labor resources. At its center should be a national platform for interaction between labor market participants - government agencies, educational institutions, enterprises, and candidates - that implements the functions of a single access interface (web interface and mobile clients), a user registration and authentication module (integration with the national electronic identification system), a vacancy and resume management module, and a module for verifying educational and professional qualifications (digital certifications/ verified certificates). Such a platform should be built on the principles of open architecture (API-first), microservice orchestration and the use of standardized data formats (for example, structured CVs), which will ensure interoperability with state information resources, corporate applicant tracking systems (ATS) and international recruitment portals.

Table 2: Conceptual system for attracting labor force to industrial enterprises in Ukraine based on digital technologies [8] - [11].

Stages of engagement	Digital tools	Digital tool functions
1) Search and selection of personnel	▪ single national digital employment platform; ▪ AI recommendations; ▪ gamified competency tests.	▪ integration of public and private job databases; ▪ algorithms for selecting vacancies by skills; ▪ quick check of technical and soft skills.
2) Automation of HR processes	▪ applicant tracking systems (ATS); ▪ video interviews with AI analytics; ▪ HR chatbots.	▪ automatic resume selection; ▪ interview scheduling, hiring analytics; ▪ initial screening and response to candidates 24/7.
3) Motivation and retention of personnel	▪ mobile applications for employees; ▪ E-learning systems (LMS); ▪ personalized development trajectories.	▪ access to salary, bonuses, corporate news; ▪ online courses adapted to the company; ▪ AI-building of career plans.
4) Labor market analytics	▪ big data & predictive analytics; ▪ management dashboards; ▪ scenario modeling.	▪ forecasting staffing needs; ▪ visualizing staff turnover, productivity; ▪ simulating the impact of automation on staff.
5) International integration	▪ E-visa and migration services; ▪ international recruitment exchanges (LinkedIn, EURES); ▪ digital adaptation programs for migrants.	▪ simplified recruitment of foreign workers; ▪ access to the global human resources market; ▪ mobile applications with language and legal support.

The key element of the selection mechanism is the intelligent recommendation module, which combines multi-level selection algorithms: semantic analysis of job descriptions and resumes, skills profiling using professional competence parameters, machine learning models for predicting employee success in the position and multi-criteria ranking mechanisms taking into account geographical, social and motivational factors. Candidate assessment systems should include gamified tests for measuring technical skills and cognitive indicators, standardized situational tools for assessing behavioral competencies, as well as knowledge testing technologies in the "production task simulator" mode.

Automation of HR processes involves the integration of corporate ATS with the internal logic of the enterprise: routing of candidates (their documents), automatic scheduling of interviews, calendar management, collection of recruitment funnel analytics and reporting on key indicators. Video interview technologies should be supplemented with analytical modules – automatic transcription, semantic analysis of responses, tools for assessing communication skills and adaptation for remote platforms – while the use of methods for automatic interpretation of non-verbal signals should be accompanied by validation procedures, human control and transparent documentation of the methodology to minimize the risks of bias and incorrect conclusions. Chatbots and automated assistants serve as the first point of contact: they conduct initial screening, inform candidates about requirements, assist with document submission, and facilitate rapid communication, but the hiring decision should remain with the human dispatcher.

HR process automation involves integrating corporate ATS with the internal logic of the enterprise: routing candidates (their documents), automatic interview scheduling, calendar management, collecting analytics of the hiring funnel and reporting on key indicators. Video interview technologies should be supplemented with analytical modules - automatic transcription, semantic analysis of responses, tools for assessing communication skills and adaptation for remote platforms - while the use of methods for automatic interpretation of non-verbal signals should be accompanied by validation procedures, human control and transparent documentation of the methodology to minimize the risks of bias and incorrect conclusions. Chatbots and automated assistants play the role of the first point of contact: they conduct initial screening, inform candidates about the requirements, help with submitting documents and facilitate rapid communication, but the hiring decision should remain with the human dispatcher.

To increase employee motivation and retention, the system offers a mobile “employee cabinet” that aggregates information about working conditions, payments, bonus programs, individual development trajectories and continuous learning opportunities. The LMS module integrates with the platform and provides modular training courses, certification tracks, adaptive learning paths with elements of micro-learning and testing in a production context; employee development is accompanied by electronic “career maps” that are automatically updated based on completed courses and performance assessments, and AI modules offer personalized training recommendations. This approach minimizes information asymmetry between the employee and the employer and promotes internal personnel transfers and retraining.

The analytical module is a data warehouse and analytics array (data warehouse/ data lake + BI/visualization) that collects and aggregates administrative, industrial and educational data to build predictive models of labor force needs. The use of Big Data and predictive analytics allows you to model the dynamics of demand for professions, identify clusters of competencies, predict shortages by region and technological profiles, as well as simulate scenarios of the impact of automation and changes in production chains on the need for labor. Dashboards (information panels) for management should display a set of KPIs (performance indicators), which will ensure prompt decision-making and long-term planning. In the context of international integration, the system should support modules for electronic coordination of migration procedures, interaction with international labor exchanges and verification services of foreign qualifications, as well as digital adaptation services - multilingual mobile guides, access to legal and medical information, platforms for finding housing and social support. For verification of documents and certificates, it is advisable to use distributed registry technologies (verifiable credentials) ensuring privacy and user control over their own data.

The implementation of such a system requires a legislative basis [12] of regulatory and organizational support: defining the legal framework for data exchange, rules for personal data processing and algorithmic transparency, standardization of data formats, cybersecurity guarantees and mechanisms for auditing algorithms.

5 CONCLUSIONS

The effectiveness of labor force involvement in the use of digital technologies directly depends on the ability of industrial enterprises and society to adapt to the challenges of modernity. Only with a comprehensive approach to the formation of employment strategies is it possible to achieve a balance between technological progress and the well-being of employees, which is the basis of sustainable economic growth and social stability in Ukraine.

The main results of the study are as follows: a holistic conceptual system for attracting the workforce of industrial enterprises has been developed, with the functions of each technological element highlighted; the relationship between the digital transformation of HR processes and increasing the sustainability, productivity and personnel competitiveness of industrial enterprises has been substantiated; key areas of practical integration of digital tools into the human resources management system have been identified.

For the gradual implementation of the presented conceptual system, industrial enterprises of Ukraine are recommended to: gradual deployment of a digital recruitment infrastructure; automation of key HR processes; implementation of platforms for employee training and development; creation and active use of an information and analytical HR database based on an analysis of the labor market and qualification requirements, competencies and career trajectories of employees for forecasting needs in human resources and planning recruitment.

The expected results of implementing the presented proposals are: reduction of the hiring period from several months to a few weeks; reduction of recruitment costs; increase in labor productivity due to targeted personnel selection; formation of a positive brand of industrial enterprises as employers; ensuring sustainable development of industry by improving the quality of labor potential.

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Digital Technologies in the Economic Security Management System of Industrial Organizations: Business Process Modeling

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Keywords: Economic Security, Digital Technologies, Industry 4.0, Business Process Modeling, Industrial Organizations, ERP-System, Big Data Analytics, Blockchain.

Abstract: The development of the Industry 4.0 concept and the intensive digitalization of business processes of industrial organizations create qualitatively new conditions for managing their economic security. Traditional protection methods are becoming insufficiently effective in the face of rapidly changing threats associated with cyberattacks and data integrity risks. The purpose of the study is to develop theoretical and methodological principles and a practical model for integrating digital technologies into the economic security management system of industrial enterprises through the prism of business process modeling. The work uses a systems approach, a process approach, regression analysis and modeling methods. The authors propose a process-oriented model for ensuring economic security, which involves the use of technologies such as ERP systems, Big Data Analytics and blockchain to ensure transparency and continuity of critical business processes (for example, supply chain management and production). The results of the study show that the implementation of integrated digital solutions not only increases efficiency and productivity (up to 15-20%), but also significantly strengthens the ability of the enterprise to withstand internal and external threats through real-time monitoring and risk prediction. The practical significance of the work lies in the possibility of using the proposed model by industrial organizations to develop digital transformation strategies taking into account aspects of economic security.

1 INTRODUCTION

The contemporary global economy is defined by rapid digitalization and geopolitical volatility. For Ukrainian industrial organizations seeking competitiveness and sustainable development, embracing digital transformation – incorporating technologies like the Internet of Things, AI, Big Data, and Cloud Computing – is essential. This shift fundamentally optimizes business processes, making them more flexible, efficient, and cost-effective.

Crucially, this digital evolution simultaneously introduces a new generation of sophisticated threats, creating a critical gap in traditional economic security management. The problem lies in the fact that while digital technologies dramatically enhance operational efficiency, they simultaneously introduce significant vulnerabilities that traditional, reactive security models are ill-equipped to handle:

1) The extensive reliance on interconnected digital infrastructure and data creates a massive attack surface for cyber threats.
2) The sheer volume of data and complex information systems increases the risk of data manipulation, insider threats, and breaches, which can directly lead to significant financial and reputational damage.
3) Over-reliance on complex information systems creates potential single points of failure, turning technological dependence into a critical economic security risk.

The central challenge in the digital age is the mismatch between the rapidly evolving complexity of digital threats and the current, reactive approach to economic security. To ensure sustainable operations, security must transition from a simple protective function to a proactive, integrated strategy embedded directly into core business processes. Therefore, there is a critical need for methodological tools, such as business process modeling techniques, to enable industrial organizations to seamlessly integrate digital security mechanisms into their operational models, thereby effectively managing economic security within the complex digital economy.

2 LITERATURE REVIEW

The impact of digital transformation on businesses is a highly relevant and complex issue, making it a frequent subject of academic research. In recent decades, have studied how digital transformation affects the economy, politics, and culture, particularly focusing on artificial intelligence (AI), the Internet of Things (IoT), and big data [1] - [3], [11], [17]. Furthermore, [1] emphasize that to truly achieve innovative solutions in business digitalization, enterprises need to integrate blockchain, AI, and the industrial IoT, as the combined potential of these technologies is greater than their individual capabilities.

Digitalization is transforming businesses in two key ways: by boosting productivity and by paving the way for fully digital enterprises [5] - [8]. Across EU countries, the digital economy is increasingly driven by the use of data analytics and artificial intelligence (AI) to fuel economic growth and innovation [2]. This digital shift enables companies to optimize production, cut costs, and increase profits [9].

AI has significantly upgraded digital tools, turning them from simple communication methods into sophisticated instruments for data analysis, automation, and industrial decision-making. This is seen in applications like voice assistants, image recognition, autonomous vehicles, robotics, and predictive analytics [11]. Complementing this, Blockchain technology provides a secure, transparent, and trustworthy base for business intelligence by ensuring data integrity and transparency. Its combination with AI is creating novel solutions in critical areas such as supply chain management, finance, and enterprise production structures [10].

While digitalization fosters financial accessibility, broader economic opportunities, and innovation, it also generates regulatory uncertainty, cybersecurity risks, and technological limitations. To strengthen economic security and trust within the digital economy, [3], [12], [14] advocate for prioritizing measures such as regulatory clarity, risk-based regulation, robust cybersecurity, and enhanced consumer education.

Digital transformation significantly increases the efficiency of industrial enterprise management through automation, data analytics, and process integration into a single digital ecosystem, which allows you to optimize business processes, reduce costs, speed up decision-making, and increase the competitiveness of the enterprise [15] - [18]. The practical application of digital technologies at industrial enterprises allows for faster response to market changes, improved product quality, and effective resource management.

The extensive research on digital transformation has not yet fully clarified how digital technologies influence the security of economic and private organizations. Because current methods for measuring economic security don't adequately address the digital environment's unique characteristics, it's crucial to develop comprehensive, integrated approaches. These new methods must merge conventional financial metrics with specialized indicators for cybersecurity and digital system resilience.

3 METHODOLOGY

To achieve the goal, a systematic and process-oriented approach was used. Economic security is considered as an integrated system that encompasses financial, human resources, information and management components. Business process modeling was carried out based on the Business Process Modeling Notation methodology with an emphasis on critical control points, where digital technologies introduce the greatest changes and risks. The business model for economic security management is proposed to be implemented through the integration of three key digital circuits into the standard business process of an industrial organization [16]. The entire cycle is a dynamic system where ERP provides Continuity and process control; Big Data Analytics provides Forecasting and detection of hidden threats; and Blockchain guarantees Transparency and immutability of data in the supply chain. The entire cycle is aimed at transforming risk information into a tangible economic advantage, strengthening the enterprise's ability to withstand threats in real time (see Fig. 1).

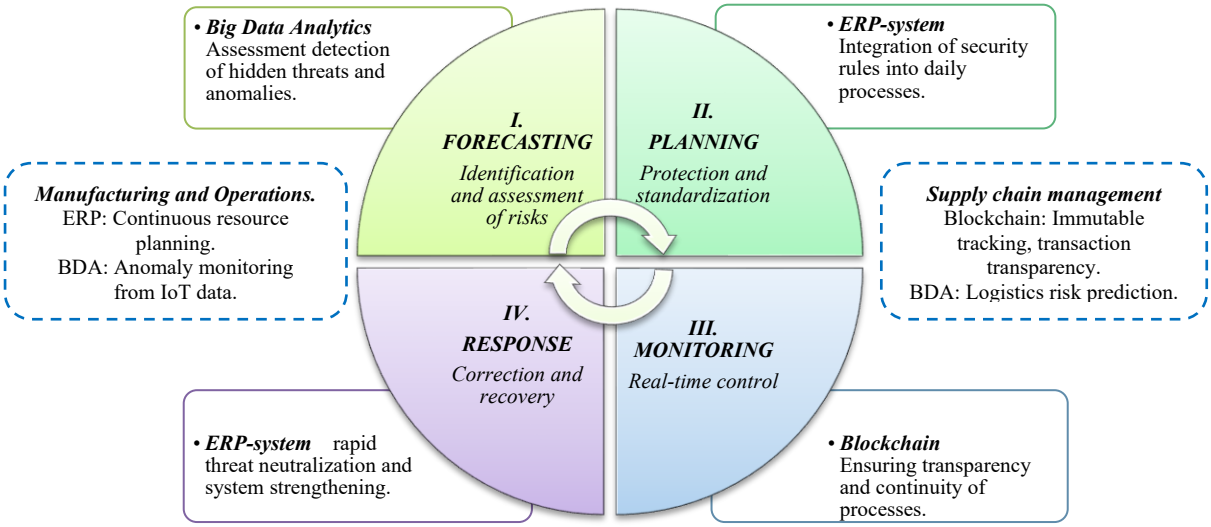


Figure 1: Process-oriented model of economic security of industrial organizations.

The business model allows you to adjust, change the system, eliminate its shortcomings before it is physically implemented, allows you to reduce the costs of creating a system, makes it possible to evaluate work based on results, helps to achieve mutual understanding between all project participants. At the same time, it should be understood that various modeling languages are used to model the business processes of organizations, each of which cannot always be adapted, especially to complex industrial organizations [15].

4 RESULTS AND DISCUSSION

The digital economy, which includes new digital industries and old ones revamped by technology, is a major driver of both economic growth and social change. This current phase of development is often called the Fourth Industrial Revolution because it features rapid changes and close interaction between production and digital technologies, leading to more intellectualized labor [9].

The exponential growth of data volumes generated by enterprises poses a challenge to traditional methods of information processing and requires the development of new innovative solutions. Digital transformation is more than just adopting new technologies like AI, the Internet of Things (IoT), cloud computing, blockchain (for things like cryptocurrency), augmented/virtual reality, and biometrics. According to [2], it fundamentally requires a complete overhaul of a business's management system, from setting strategic goals to putting them into action. This includes developing and launching new business ideas and often revising those original goals. For this transformation to succeed, an organization must be flexible and able to quickly adapt to change, effectively using these new digital tools to tackle complex problems. While offering many benefits, this process also brings new challenges: businesses must constantly keep up with rapid technological changes, enhance cybersecurity, and manage vast amounts of data.

The use of formalized business process models (BPMN, IDEF0, ARIS) made it possible to carry out a structural decomposition of the activities of industrial enterprises, accurately identifying critical control points and potential bottlenecks where threats to economic security may arise, and thus develop mechanisms for preventive risk prevention. Additionally, the use of statistical analysis of the dynamics of digitalization of Ukrainian enterprises for 2020–2025 (growth from 28% to 55%) in combination with Eurostat data on EU countries (growth from 61% to 82%) creates a benchmarking base for assessing the digital divide and substantiating the need to implement integrated digital solutions (such as ERP, BDA, Blockchain) as a significant factor in strengthening ES and increasing competitiveness. Both data series demonstrate a stable and predictable linear growth of digitalization, as confirmed by $R^2 > 0.99$. This suggests that the selected linear regression model is

very well suited to describe digitalization trends in both the EU and Ukraine over this time interval (see Fig. 2) [5], [19].

The European industrial sector is currently experiencing major shifts due to a mix of global and internal pressures. These factors include the complete digitalization of society, greater environmental awareness, an aging workforce, a shortage of skilled labor, and changes in international trade leading to increased competition, particularly from Asia. To survive, European industry must adapt to these new realities [5].

Merging digital tools with reality lets us build virtual models that accurately reflect real-world conditions. This enables firms to test and improve products earlier, leading to significant cost reductions. Moreover, when industrial enterprises prioritize fast learning, innovation, and flexible operations, they can quickly adjust to the market, keep costs low, improve how they're managed, and ensure stable economic security.

Digital transformation drives industrial growth, using technologies like AI and robotics to increase productivity and lower costs. Critically, a firm's economic security is now less isolated and more dependent on its position within the entire network of economic relationships [14].

We will model the impact of the implementation of digital technologies on the financial indicators of Novikon LLC in order to quantitatively assess productivity growth, cost reduction and risks to determine additional profit, ROI and payback period of investments [15], [20]. The calculation results shown in Table 1 show that the digitalization of business processes in Novikon LLC provides a quick payback of investments (1.3–1.7 years) and a high level of profitability (ROI 58–80%), which indicates a significant potential for increasing the efficiency and economic security of the enterprise through the implementation of digital technologies.

The obtained calculation results confirm the high economic feasibility of digitalization, because even in a conservative scenario, the implementation of IT solutions provides a quick payback and a significant increase in profitability. This indicates that business process automation effectively optimizes costs and increases productivity, although the final benefit significantly depends on the accuracy of the initial parameters - margin, OPEX level and ERP implementation cost.

Optimizing digital tool selection requires assessing an enterprise's size, production specifics, and available budget [18]. The foundation for robust cyber threat protection lies in a holistic approach that integrates multiple tools and mandates continuous personnel training. Industrial enterprises employ a broad spectrum of digital defenses to ward off cyberattacks, with the principal tools being highlighted in Figure 3.

Digital process automation uses technologies to minimize common manual errors, leading to highly accurate and reliable task completion. Beyond accuracy, these technologies also enhance collaboration among participants, boost work efficiency, and cut labor costs. However, the impact of digital technologies varies greatly depending on the industry and a company's current readiness for digital transformation. For instance, goods-producing enterprises have longer production cycles, which means their return on investment (ROI) from digital technologies takes more time. Despite this, they actually implement a broader range of digital optimization and automation technologies in their production processes compared to service-providing companies.

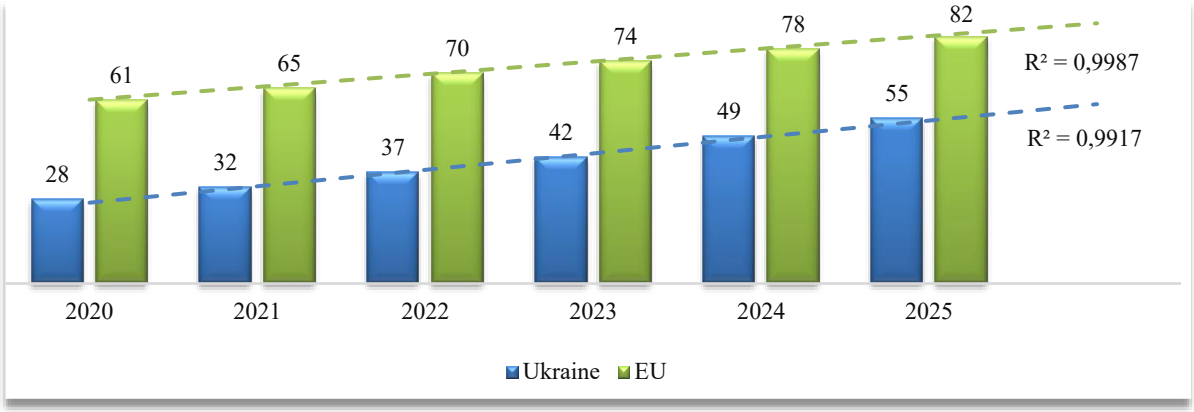


Figure 2: Digitalization of Ukrainian and EU industrial enterprises, % (2020–2025) [5].

Table 1: Scenario analysis for the digitalization model of economic security management using the example of Novicon LLC.

Indicator	Conservative	Average	Optimistic
CAPEX (₴)	500000	1500000	3000000
ΔR (%)	0,05	0,1	0,15
ΔOPEX (%)	0,07	0,12	0,18
ΔLoss (%)	0,3	0,5	0,7
R_0 (₴)	19097100	19097100	19097100
GP_0 (₴)	5729130	5729130	5729130
NP_0 (₴)	266800	266800	266800
$OPEX_0$ (₴)	5462330	5462330	5462330
$Loss_0$ (₴)	381942	381942	381942
R_1 (₴)	20052955	21006810	21961665
GP_1 (₴)	6015887	6302043	6588500
$OPEX_1$ (₴)	5083964	4811850	4476713
$Loss_1$ (₴)	267360	190971	114583
NP_1 (₴)	664563	1299222	1997204
ΔNP (₴)	397763	1032422	1730404
ROI (%)	0,796	0,688	0,577
Payback (y)	1,26	1,45	1,73

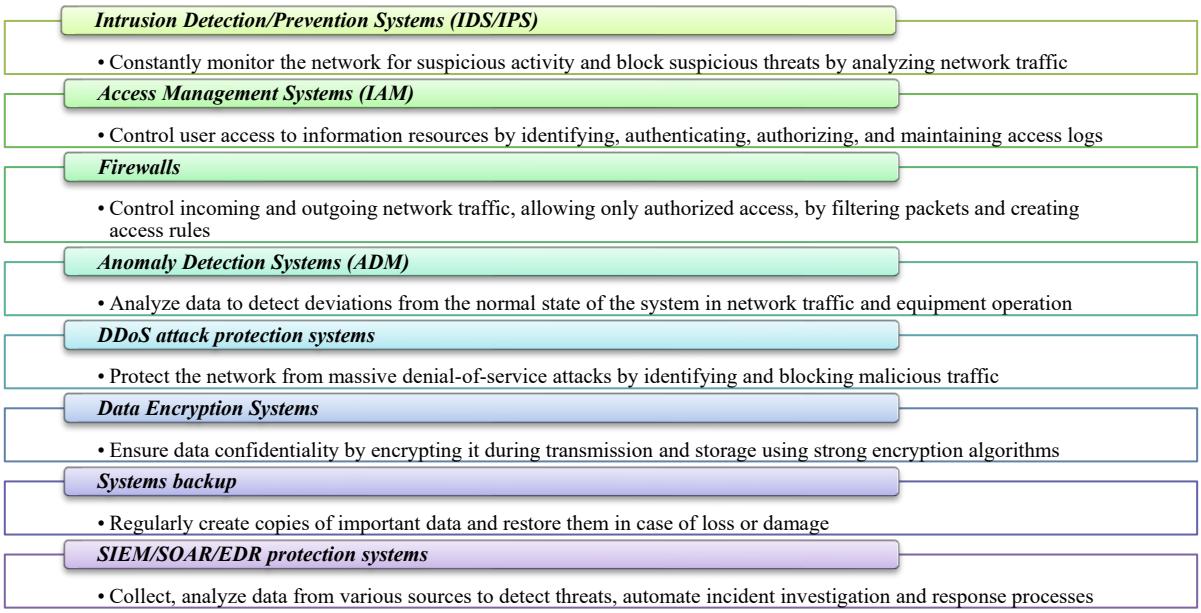


Figure 3: Digital enterprise security tools.

5 CONCLUSIONS

Digital transformation is essential for modern industrial progress, driving efficiency, product innovation, and market responsiveness to secure competitive advantages. However, this transition is inherently complicated by a heightened risk landscape, including serious concerns regarding privacy violations and the proliferation of information technology fraud and cybercrime. This study was specifically designed to support the industry's digital transformation by systematically assessing the current state of digital tool utilization in economic security management and identifying critical areas for improvement in cyber protection.

The core contribution is the affirmation that economic security management must adapt to the comprehensive operational changes introduced by digitalization across all production and value-

creation stages. The research results confirm the need for industrial enterprises to:

1) Recognize that the benefits of digital growth are inseparable from increased security risks;
2) Systematically analyze the profound, cross-functional changes digitalization introduces.

Ultimately, the study validates the crucial requirement for integrating modern cyber protection strategies, demonstrating that while digital technologies optimize operations and enhance transparency, addressing the pressing problem of economic security in this digitized environment remains a vital necessity for all enterprises, demanding further scientific and practical investigation.

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Financial Data Analysis Using CNN With Feature Selection

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Keywords: Convolutional Neural Network (CNN), Feature Selection, ANOVA, Mutual Information (MI), Chi-Square.

Abstract: In the age of big data, the financial services industry generates massive volumes of complex and high-dimensional data that demand advanced analytical solutions. Convolutional Neural Networks (CNNs), originally developed for image analysis, have demonstrated strong capabilities in learning rich, hierarchical features directly from raw financial data, making them well-suited for tasks such as credit scoring, fraud detection, and risk assessment. This paper presents a proposed CNN model tailored for financial data analysis. The model efficiently captures the underlying patterns and nonlinear relationships within the data, which is considered one of the reasons for the model's high accuracy. To further enhance performance, a feature selection (FS) step was integrated before training, enabling the model to focus on the most informative attributes. Experimental results on the Santander Customer Transaction Prediction dataset show that the proposed CNN model, when combined with feature selection, achieved a remarkable 100% accuracy in classification tasks. These findings underscore the potential of CNN-based frameworks, enhanced by targeted feature selection, to transform financial data analysis. The approach enables more accurate, scalable, and automated decision-making across critical financial sector applications.

1 INTRODUCTION

Before the 1996 launch of the first internet banking application in the US by Citibank and Wells Fargo Bank, banks exclusively offered in-person services to their clients [1]. The adoption of online credit card usage followed the launch of internet banking. Over the past ten years, this has grown significantly, and services like social networking, online banking, working from home, e-commerce, and online payment systems have also been launched and are now extensively utilized [2]. In today's data-driven financial landscape, understanding and anticipating customer behavior is critical for businesses seeking to enhance decision-making, improve customer experiences, and reduce operational risks [3]. One of the most significant applications of artificial intelligence (AI) in this domain is customer transaction prediction, which involves forecasting future financial activities based on historical transaction data. Accurate transaction prediction supports a wide range of strategic objectives, including personalized marketing, dynamic credit scoring, fraud detection, and inventory optimization [4]. With the explosive growth in digital transactions and the increasing complexity of consumer behavior, traditional data analysis and machine learning techniques often fall short in extracting deep insights from high-dimensional and sequential transaction data [5]. This has led to a growing interest in deep learning approaches, particularly Convolutional Neural Networks (CNNs), which have demonstrated exceptional capabilities in capturing hidden patterns, temporal dependencies, and contextual relationships within large datasets [6]. CNNs, originally designed for image recognition tasks, are now being adapted to structured financial data for their ability to automatically learn hierarchical features without the need for manual feature engineering. When applied to customer transaction prediction, CNNs treat transaction histories as structured inputs such as time series matrices or event sequences and process them through layered convolutional operations to extract meaningful insights [7]. This study explores the use of a proposed CNN-based model for predicting customer transactions. By leveraging the power of deep feature extraction and integrating effective data preprocessing techniques, the model aims to achieve high prediction accuracy and generalizability across varied customer segments.

The remainder of this paper is organized as follows: Section 2 reviews related work in transaction prediction and deep learning applications. Section 3 presents the methodology and the proposed CNN model architecture. Section 4 provides the results and performance analysis, followed by conclusions and future work in Section 5.

2 RELATED WORKS

In recent years, the increasing availability of digital financial data has driven substantial research interest in customer transaction prediction. Traditional approaches have largely relied on statistical models and classical machine learning techniques such as logistic regression, decision trees, and support vector machines to forecast transaction patterns and customer behavior. While these methods provide a foundation for predictive modeling, they often struggle to capture the complex, nonlinear, and temporal dependencies inherent in transaction data. With the emergence of Artificial Intelligence (AI) and deep learning, more sophisticated models have been proposed to address these limitations. In particular, Convolutional Neural Networks (CNNs) have gained attention for their ability to automatically learn multi-level features from raw or minimally processed data. Originally applied in computer vision tasks, CNNs have since been adapted for financial applications, including fraud detection, credit scoring, and transaction categorization, due to their high accuracy, scalability, and end-to-end learning capabilities. This section provides an overview of the existing literature on customer transaction prediction, highlighting both conventional and deep learning-based approaches. It focuses on how AI techniques, particularly CNNs, have been leveraged to improve prediction accuracy and adapt to large-scale, real-time financial environments. The review also identifies key research gaps and motivations for the development of the proposed CNN model introduced in this study.

A. Chouiekh and E. Ibn El Haj [8] used deep convolutional neural networks to detect and classify customer loss using a labeled dataset of 18,000 prepaid users. The method was based on call detail records from a telecom company. The researchers found that DCNN outperformed other machine learning techniques with an accuracy of 89%, demonstrating the effectiveness of this approach. M. Nabipour et al. [9] compared two deep learning techniques, Recurrent Neural Network (RNN) and Long Short-Term Memory (LSTM), with nine machine learning models. The input values were 10 technical indicators from ten years of historical data. The results showed that RNN and LSTM performed significantly better than other prediction models for continuous data, with an accuracy of 87%. M. Pondel et al. [10] presented a deep learning model for predicting client attrition in e-commerce, focusing on real data with 75% of buyers being one-time customers. The model showed promise with 74% accuracy, 78% precision, and 68% recall, indicating potential for increased client retention and improved business performance. However, the prediction method may be erroneous. A. Khattak et al. [11] provided a successful strategy for predicting customer turnover based on a hybrid deep learning model known as BiLSTM-CNN. The goal is to effectively estimate customer turnover using benchmark data while also improving the accuracy of the churn prediction process. The experimental results reveal that when trained, tested, and validated on the benchmark dataset, the proposed BiLSTM-CNN model achieved a remarkable 81% accuracy. C. Ku et al. [12] suggested combining investors' expertise with a Long-Short-Term Memory (LSTM) algorithm to predict stock prices. The strategy involves gathering technical indicators from investors and using them as input to the LSTM model. The model is trained and evaluated on a dataset of 100 stocks, and its accuracy is measured using parameters like average forecast accuracy, average cumulative return, Sharpe ratio, and maximum drawdown. The simulation results show that the proposed model outperforms other strategies in terms of accuracy (57%), highlighting the potential of integrating investor knowledge with machine learning algorithms. J. Li et al. [13] developed a CNN-LSTM and attention mechanism-based credit risk prediction model for listed businesses. This method combines a CNN model with an LSTM model for long-term time-series prediction, reducing data complexity, increasing training and calculation speeds, and resolving historical data gaps. The model also includes an attention mechanism for optimization. The model achieved an accuracy of 98.43%, making it a significant contribution to credit risk prediction in listed businesses. O. Seymen et al. [14] compared various machine learning techniques for predicting future customer loss in the retail sector. The deep learning model based on CNN performed better in classification, with a 97.62% accuracy rate compared to the ANN with 96%. The study highlights the importance of deep learning in churn prediction. Table 1 shows the summary of these works.

The proposed CNN model aims to solve several limitations identified in prior research. First, it is

designed to be domain-independent, allowing applications across various sectors, including telecom, retail, e-commerce, and finance. To address low recall and prediction errors seen in earlier models, we apply optimized preprocessing, class balancing, and regularization. Unlike complex hybrid models, the proposed model's architecture remains lightweight yet powerful, reducing training time without sacrificing accuracy. The proposed model also eliminates reliance on external expert inputs, making the model fully autonomous. By avoiding excessive model complexity, we ensure fast computation, making it suitable for real-time deployment. Feature selection is used to improve learning efficiency and reduce noise. The model is optimized for performance even in unbalanced or sparse datasets. It also generalizes well to unseen customer behaviors. Overall, the proposed CNN approach offers a scalable, accurate, and adaptable solution for customer transaction prediction.

3 METHODOLOGY

The proposed customer transaction prediction system, as shown in (Fig. 1), based on the proposed CNN, begins with the Santander dataset, which is first split into training and testing sets, followed by a data preprocessing stage to ensure quality input. Feature selection is then conducted using three techniques: Mutual Information, Chi-Square, and ANOVA to extract the most informative features and reduce dimensionality. These selected features are fed into a deep Convolutional Neural Network (CNN) composed of multiple convolutional layers with increasing filter sizes (16 to 1024), activated by Leaky ReLU to overcome vanishing gradients. Max-pooling layers reduce feature map dimensions, followed by a flattening step and fully connected dense layers. A softmax activation function at the output layer classifies the transaction outcome. Training is conducted on features selected by Mutual Information and Chi-Square, while ANOVA-selected features are used in the testing phase to evaluate performance. This architecture aims to enhance predictive accuracy and overcome limitations of previous models by integrating robust feature selection with deep learning.

3.1 The Dataset Description

The dataset used in this study originates from the Santander Customer Transaction Prediction challenge hosted on Kaggle by Banco Santander. It contains over 200,000 records and 200 anonymized numerical features, with a binary target variable indicating whether a customer has made a specific transaction (1) or not (0). Due to anonymization, the feature names and descriptions are unavailable, making this dataset ideal for experimenting with different feature selection techniques. The data poses several real-world challenges common in financial datasets, including high dimensionality, potential multicollinearity among features, and imbalanced class distribution. These complexities make it a strong benchmark for evaluating how feature selection methods can help reduce redundant data, enhance model interpretability, and improve predictive performance. Before applying feature selection and classification, the data[1] undergoes preprocessing steps such as handling missing values, scaling features, and splitting into training and testing sets to ensure reliable evaluation.

3.2 Dataset Splitting (1st Stage)

To ensure robust model evaluation and avoid overfitting, the provided dataset is divided into two main subsets training set and the testing set. Specifically, the biggest amount of the data is used for training the model and optimizing its parameters, while the remaining is reserved for testing and evaluating the model's predictive accuracy [15]. In this work, the Santander Customer Transaction Prediction dataset is divided into training and testing subsets using a 70:30 ratio to ensure reliable evaluation and reduce the risk of overfitting. The training set, comprising 70% of the data, is used to develop and optimize the predictive model, while the remaining 30% is reserved exclusively for testing to assess the model's performance on unseen data. This split allows for a balanced approach to model validation and performance benchmarking. Cross-validation techniques are applied during the training phase to further ensure that the model generalizes well across different subsets and is not tailored only to the training data. This method supports robust performance assessment, which is critical when working with high-dimensional, anonymized financial data like this.

[1]The dataset https://www.kaggle.com/competitions/santander-customer-transaction-prediction/data?select=train.csv](https://www.kaggle.com/competitions/santander-customer-transaction-prediction/data?select=train.csv).

Table 1: Summary of related works.

Ref. No.	Year	Author	Technique	Dataset	Accuracy	Limitations
[8]	2020	A. Chouiekh and E. Ibn El Haj	Deep CNN	Call detail records (18,000 prepaid users)	89%	Limited to telecom data; not compared on diverse datasets
[9]	2020	M. Nabipour et al.	RNN & LSTM	10 years of technical indicators	87%	Limited to continuous stock data; requires large historical datasets
[10]	2021	M. Pondel et al.	Deep Learning	E-commerce customer data	74%	The prediction method may be erroneous; lower recall (68%)
[11]	2023	A. Khattak et al.	BiLSTM-CNN	Benchmark churn dataset	81%	Lacks generalizability across domains
[12]	2023	C. Ku et al.	LSTM with investor expertise	100 stocks data	57%	Low accuracy; relies on expert knowledge input
[13]	2023	J. Li et al.	CNN-LSTM + Attention	Listed business financial data	98.43%	Focused on credit risk only; high model complexity
[14]	2023	O. Seymen et al.	ANN + CNN	Retail customer data	ANN: 96% CNN: 97.62%	ANN needs further optimization

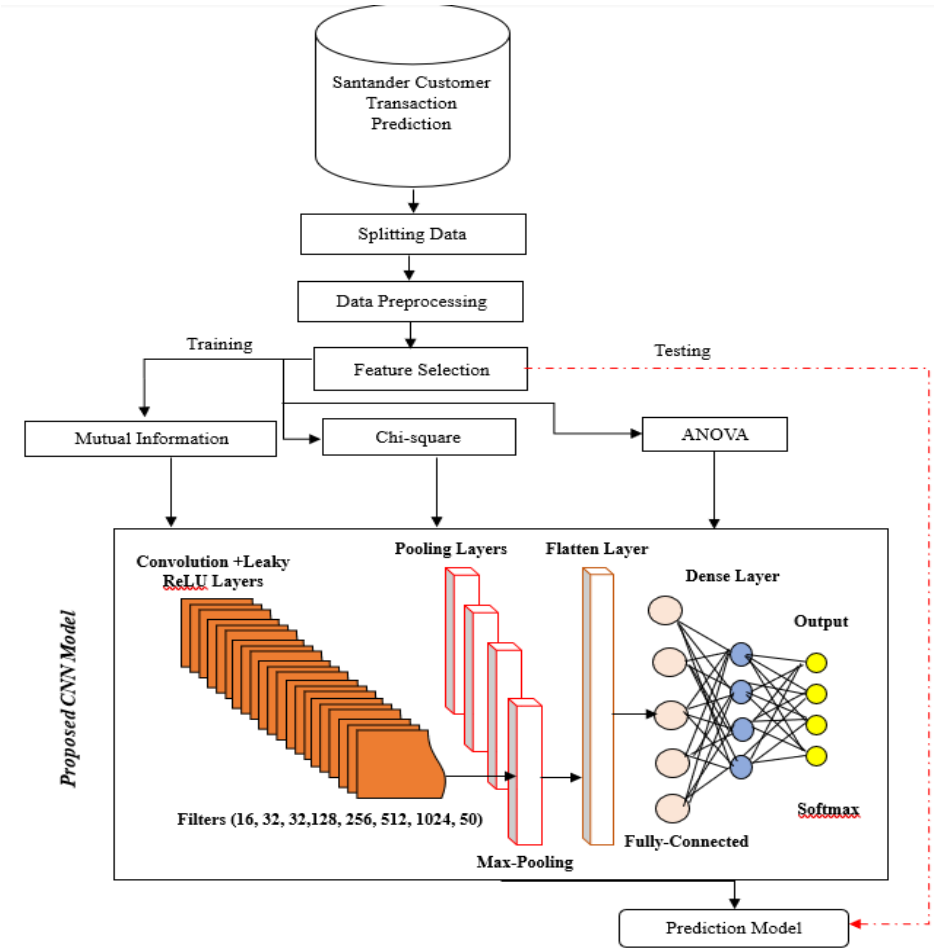
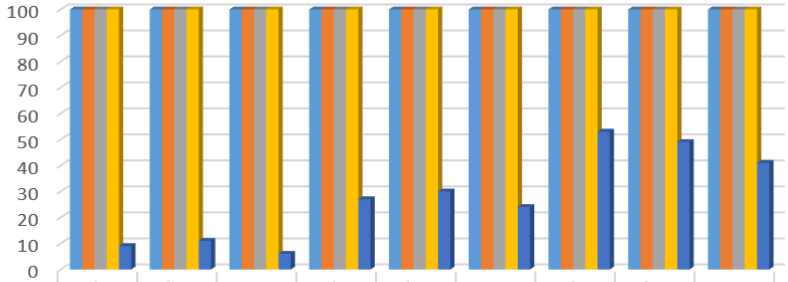


Figure 1: The proposed system architecture.



	mi10	ch10	nova10	mi30	ch30	nova30	mi50	ch50	nova50
prs	100	100	100	100	100	100	100	100	100
rec	100	100	100	100	100	100	100	100	100
f1	100	100	100	100	100	100	100	100	100
acc	100	100	100	100	100	100	100	100	100
time in second	9	11	6	27	30	24	53	49	41

Figure 2: The proposed CNN model results comparison.

3.3 Preprocessing Stage (2nd Stage)

This stage includes some of the processes as follows:

1) Missing Value [16]. To ensure the quality and consistency of the data used in this work, missing values in the Santander Customer Transaction Prediction dataset are carefully handled during the preprocessing phase. Although the dataset is generally clean and anonymized, any missing entries are addressed to prevent issues during model training. If missing values are found, they are either imputed using statistical techniques such as mean or median imputation, depending on the distribution of the feature, or, in the case of minimal missingness, the affected rows may be removed entirely. This step is essential to maintain the integrity of the data, ensure reliable model learning, and avoid introducing bias or distortion into the prediction results.
2) Normalization. One of the initial processing steps for processing the dataset is applied before the data is used, such as increasing or decreasing the range of values. Normalization is convenient and useful in dataset problems that depend on classification, the conversion of feature values for a specific and small range, such as 0 to 1. There are many ways to normalize, such as Z-normalization and Min-Max.

Normalization. Min-Max Normalization is a linear transformation technique used in processors in which preserving the relationship between the original dataset is important. In addition, it is considered one of the simple techniques that are suitable for the dataset within predefined limits [17], [18]. Normalization is done according to (1).

$$x\ new = \frac{x - \min(x)}{\max(x) - \min(x)}. \quad (1)$$

Where x new represents the normalized x. While the dataset contains 200 anonymized numerical features with potentially varying scales and distributions, normalization is used to rescale the values to a common range typically between 0 and 1 or to a standard normal distribution (zero mean and unit variance). This process prevents features with larger numeric ranges from dominating the learning process and helps many machine learning models, especially those based on distance or gradient-based optimization (like CNNs), to converge faster and perform more accurately. By applying normalization, the training process becomes more stable, and the model achieves better generalization on unseen data.

3.4 Feature Selection Stage (3rd Stage)

For customer transaction prediction, effective feature selection plays a vital role in improving classification performance and computational efficiency. In our work, we aim to identify the most informative features from the high-dimensional Santander dataset, which contains 200 anonymized numerical attributes. Not all features contribute equally to the prediction task; some may be redundant or irrelevant. To address this, three distinct feature selection techniques were applied in the proposed model to evaluate and rank feature importance. This process involves assessing each feature's contribution to distinguishing between customers who perform a transaction (class 1) and those who do not (class 0). By retaining only the top "k" features based on their significance scores, we eliminate noise, reduce dimensionality, and enhance model interpretability

and training speed. This targeted selection ensures that the classifier focuses on the most predictive patterns, thereby boosting overall accuracy.

3.4.1 Select Features Based on the Mutual Information Technique

Mutual information is frequently used in feature selection because it can identify non-linear interactions between numerous variables. The majority of mutual information-based feature selection methods use the two (2) and (3), which compute the relevance of a feature subset and redundancy, respectively.

$$\mathrm{Red} = \mathrm{MI}\,(\mathrm{s}_1.\mathrm{s}_2.\ldots.\mathrm{s}_\mathrm{m}), \tag{2}$$

$$\mathrm{Rel} = \mathrm{MI}\,(\mathrm{S}.\mathrm{C}), \tag{3}$$

where C is the class label, S is the feature set, which contains m features $\mathrm{s}_1.\ldots.\mathrm{s}_\mathrm{m}$. By eliminating all unnecessary characteristics, feature selection aims to provide an ideal feature subset. Hence, the best feature subset minimizes the quality measure specified in (4).

$$\mathrm{F} = -\alpha * \mathrm{Rel} + (1-\alpha) * \mathrm{Red}, \tag{4}$$

where is used to regulate how much relevance and redundancy contribute to the fitness score [19]. In this work, Mutual Information (MI) is used as one of the primary feature selection techniques due to its effectiveness in measuring the dependency between each feature and the target variable. MI quantifies how much knowing the value of a feature reduces uncertainty about the class label, making it particularly valuable in identifying features with high predictive power. Since the Santander dataset is high-dimensional and anonymized, MI helps in uncovering non-linear relationships between features and the binary transaction outcome (0 or 1). By selecting features with the highest MI scores, we significantly reduce the number of irrelevant or redundant inputs, leading to better generalization, faster training, and improved classification accuracy. So, incorporating MI into the feature selection phase contributed to refining the model's focus on the most informative signals, which enhanced performance and interpretability.

3.4.2 Select Features Based on the Chi-Square Technique

The chi-squared test, which assesses deviation from the predicted distribution when the feature event is independent of the class value, is a numerical analysis. True positives (TP), false positives (FP), true negatives (TN), false negatives (FN), probability of a no. of positive instances (P_{pos}), and probability of the no. of negative cases (P_{neg}). There are some of the metrics used to compute the chi-square value [20].

$$\begin{gathered} chi - square = t\left(t_p\left(t_p + f_p\right)p_{pos}\right) + \\ t\left(f_n(f_n + t_n)p_{pos}\right) + t\left(f_p\left(t_p + f_p\right)p_{neg}\right) + \\ t\left(t_n(f_n + t_n)p_{neg}\right). \end{gathered} \tag{5}$$

3.4.3 Select Features Based on the ANOVA Technique

Select features based on ANOVA: For each continuous predictor, it was intended to run an ANOVA F-test to determine whether or not all of the various classes of Y have the same mean as X. Applying the following notation:

$$s_j^2 = \sum_{i=1}^{N_j}\left(X_{ij} - \bar{X}_j\right)^2 / \left(N_j - 1\right), \tag{6}$$

$\bar{x}$: The grand mean of predictor X:

$$\bar{x} = \sum_{j=1}^{J} N_j \bar{X}_j / N. \tag{7}$$

The aforementioned notations depend on pairs of (X, Y). Then, using the F statistic, the p-value is determined by p-value = Prob {F (J-1, N-J) >F}: where,

$$F = \frac{\sum_{j=1}^{J} N_j(\bar{X}_j - \bar{X})/(J-1)}{\sum_{j=1}^{J}(N_j - 1)s_j^2/(N-1)}. \tag{8}$$

A random variable called F (J-1, N-1) has degrees of freedom J-1 and N-J and follows the F distribution. A predictor's p-value should be set to zero if the denominator is zero. By ranking the predictors in ascending order depending on the p-value, the predictor is ranked. If there are ties, sort by F in order of importance first, then if there are still ties, sort by N from lowest to highest [21].

3.5 Prediction Stage Using the Proposed CNN Model

Due to its extensive network depth, CNN is categorized as a deep neural network. With each layer, CNN gains the ability to recognize a wider variety of things. Images of various resolutions are processed via image processing, with the output from each image processed and used as input to the next layer [22]. Feature selection techniques (Mutual information, Chi-square, and Analysis of Variance (ANOVA)) and classification are two distinct parts of the proposed CNN architecture. The convolutional, Leaky Rectified Linear Unit (LeakyReLU), and

pooling are the three operations following the feature selection portion [23].

3.5.1 Convolutional Layer

Among filters and data as input. To build a feature map, the filter will travel through the data and connect the input and filter value with a "dot" operation. Optimization of the convolutional layer using modified filter size, stride, and zero padding [24],

3.5.2 LeakyReLU

It is an effort to address the fading ReLU issue. When x<0, instead of being zero, a leaky ReLU will have a slight negative slope (of 0.01, or so). The equation in (9), where α is a tiny constant, is computed using the function [25].

$$f(x) = 1(x < 0)(\alpha x) + 1(x >= 0)(x). \quad (9)$$

3.5.3 Pooling Layer

The convolutional layer's output is received by the pooling layer, which also minimizes the amount of data in this layer. Filters of various sizes and strides make up the pooling layer, which travels over the feature map area. Max pooling and mean pooling are the pooling layers that are frequently used in their application [26].

3.5.4 Fully Connected Layer

Processing of the feature maps from the feature selection layers is done by the fully connected layer. In contrast to the convolutional layer, which links neurons just to certain parts of the input, the fully connected layer connects all neurons to enable linear data classification, and the fully connected layer flattens multidimensional feature map arrays into one-dimensional arrays [27].

3.5.5 Softmax Activation

A different kind of Logistic Regression, called Softmax Classifier, may classify more than two classes. The output of the last layer may be transformed to its underlying probability distribution utilizing Softmax. Softmax has the advantage that the output probability can be between 0 and 1 and that the sum of the probabilities is 1 [28].

The suggested CNN model comprised 27 layers as follows:

The nine-layer Convolutional Neural Network (CNN).

- 8 Leaky ReLU layers;
- 6 Max-pooling layers;
- 1 Flatten layer;
- 3 Dense layers.

These layers are described in further depth in Table 2.

Table 2: The suggested CNN layers.

NO.	Layer Type	Filters	Size/ stride	Activation function
1	Convolutional	16	3/1	--
2	Leaky ReLU	--	--	--
3	Max Pooling	--	1/1	--
4	Convolutional	32	3/1	--
5	Leaky ReLU	--	--	--
6	Max Pooling	--	1/1	--
7	Convolutional	32	3/1	--
8	Leaky ReLU	--	--	--
9	Max Pooling	--	1/1	--
10	Convolutional	128	3/1	--
11	Leaky ReLU	--	--	--
12	Leaky ReLU	--	--	--
13	Max Pooling	--	1/1	--
14	Dense	128	--	Linear
15	Convolutional	256	3/1	--
16	Leaky ReLU	--	--	--
17	Max Pooling	--	1/1	--
18	Convolutional	512	3/1	--
19	Leaky ReLU	--	--	--
20	Max Pooling	--	1/1	--
21	Convolutional	1024	3/1	--
22	Leaky ReLU	--	--	--
23	Max Pooling	--	1/1	--
24	Dense	1024	--	Linear
25	Convolutional	50	3/1	--
26	Flatten	--	--	--
27	Dense	2	--	Softmax

4 RESULTS AND DISCUSSION

This section displays the outcomes of applying different machine learning algorithms with and without feature selection to the Santander Customer Transaction Prediction dataset. For each scenario, the comparison highlights the most critical performance metrics: accuracy, precision, recall, F1-score, and computational time, which all demonstrate the strength and efficiency of each model. Feature selection methods such as Mutual Information, Chi-square, and ANOVA were combined in order to examine their influence on dimension reduction, classification performance, and runtime optimization. The results are then compared across the different algorithms to determine their advantages, limitations,

and trade-offs in terms of prediction accuracy. Moreover, the debate empirically examines the impact of feature selection on generalization, redundancy elimination, and addressing computational complexity. This provides more insight into what models and preprocessing methods are most suited for robust customer transaction forecasting.

4.1 Results of the CNN Model Without FS

The result in Table 3 indicates that the model without FS can achieve perfect prediction accuracy on this dataset. The tradeoff is computational efficiency; all the features require significantly more processing time. In practice, such performance can indicate overfitting or reliance on redundant/noisy features, which is why FS is still beneficial to remove complexity and to ensure the model generalizes well to new data.

Table 3: Results of the CNN model without feature selection.

	prs	rec	f1	acc	Time in seconds
Without FS	100	100	100	100	72

Table 4: Results of the CNN model with MI feature selection.

	prs	rec	f1	acc	Time in seconds
mi10%	100	100	100	100	9s
mi30%	100	100	100	100	27s
mi50%	100	100	100	100	53s

Table 5: Results of the CNN model with Chi-square feature selection.

	prs	rec	f1	acc	Time in seconds
Chi-10%	100	100	100	100	11
Chi-30%	100	100	100	100	30
Chi-50%	100	100	100	100	49

Table 6: Results of the CNN model with ANOVA feature selection.

	prs	rec	f1	acc	Time in seconds
ANOVA-10%	100	100	100	100	6
ANOVA-30%	100	100	100	100	24
ANOVA-50%	100	100	100	100	41

4.2 Results of the CNN Model with MI-FS with 10%, 30% and 50% of Features

The performance of the CNN model with Mutual Information (MI) feature selection on 10%, 30%, and 50% subsets, as shown in Table 4 exhibits consistently perfect performance with 100% precision, recall, F1-score, and accuracy for all configurations. This indicates that the CNN is very good at capturing the significant patterns in the data, even when only a subset of the features is available. For MI-10%, the model spent 9 seconds alone, which was the fastest and most efficient configuration. When the subset was increased to MI-30, the time was pushed to 27 seconds, while MI-50% further extended it to 53 seconds, reflecting the linear computation time vs feature size trade-off. There was no impact on classification performance in spite of this rise in execution time since the model still displayed perfect predictive power. This means that less carefully selected features suffice for CNN to achieve optimum accuracy. Stability in performance across all MI levels also means that there is ample redundancy in features in the dataset. Feature selection thus ensures that redundant attributes are eliminated while only the most informative are retained. Importantly, MI-10 emerges as the optimum configuration since it lowers computation without affecting accuracy. These findings underscore the effectiveness of MI in dimensionality reduction and the robustness of CNN in handling high-dimensional data. Together, the findings show that CNN in combination with MI-based feature selection can provide both computational efficiency and high accuracy.

4.3 Results of the CNN Model with Chi-FS with 10%, 30%, and 50% of Features

The CNN model with Chi-square feature selection at 10%, 30%, and 50% subsets' results are consistently perfect, as shown in Table 5, with 100% precision, recall, F1-score, and accuracy in all configurations. This suggests that, like MI, the CNN is very effective in identifying the hidden patterns of the data even when only a portion of the features is kept. At Chi-10, the model computed these results in 11 seconds, indicating computation efficiency. Increasing the subset to Chi-30 doubled the computation time to 30 seconds, and Chi-50 increased it further to 49 seconds, which indicates that larger sets of features require longer computation. However, the

consistency of prediction accuracy at all feature levels confirms that the Chi-square method successfully finds and preserves the most informative features while filtering out superfluous ones. The fact that CNN achieves the same performance with only 10% of the features shows the redundancy of the dataset and the effectiveness of Chi-square in dimensionality reduction. Even though all feature sets produced optimal results, the most optimal choice is Chi-10 because it strikes an appropriate balance between accuracy and computational cost. These findings confirm that CNN, in conjunction with Chi-square feature selection, is capable of attaining both high accuracy and effectiveness.

4.4 Results of the CNN Model with ANOVA-FS with 10%, 30%, and 50% of Features

The accuracy of the CNN model when ANOVA feature selection is applied, as shown in Table 6 proves that the model achieved its best performance in all metrics, precision, recall, F1-score, and accuracy, at 10%, 30%, and 50% subset features. When ANOVA-10 was used, the model achieved not only 100% accuracy but also the shortest computation time of just 6 seconds, which is the most cost-effective setting. As the feature count was increased to ANOVA-30 and ANOVA-50, execution time took 24 seconds and 41 seconds, respectively, without a change in performance metrics. Such robustness against subsets suggests that the CNN model is highly resilient and can maintain predictive ability even with low feature counts. Moreover, ANOVA performed well in choosing the most informative features without impacting performance despite dimensionality reduction. The results show that ANOVA-10 offers the optimal speed-accuracy trade-off and thus is an excellent choice for modeling economically. Overall, these results confirm that ANOVA-based feature selection can greatly enhance computational efficiency without sacrificing classification performance.

4.5 Comparison of CNN with Different FS Techniques

The three feature selection techniques: Mutual Information (MI), Chi-square (CH), and ANOVA, resulted in the same classification performance with perfect precision, recall, F1-score, and accuracy (all 100%) on various feature subsets (10%, 30%, and 50%) (see Fig. 2). The only variation occurs for execution time, which is then the determining criterion for choosing the best technique. At the 10% feature subset, ANOVA (NOVA10) took the least processing time of 6 seconds, which was less than MI10 (9 seconds) and CH10 (11 seconds). Similarly, at 30% and 50% subsets, ANOVA was always faster (24s and 41s) than MI (27s and 53s) and CH (30s and 49s). Since all methods share identical predictive performance, the best solution is ANOVA with 10% features (NOVA10) since it has perfect accuracy with the lowest computation expense and hence is the best option where performance and speed must be traded off.

4.6 Comparison with Related Studies

Table 7 presents a comparison of classification accuracy between previously reported studies and the proposed CNN model. Earlier works such as [8] and [9] achieved relatively high accuracies of 89% and 87%, respectively, while [10] and [11] performed moderately well with 74% and 81%, and [12] showed weaker performance at only 57% accuracy. A more advanced method in [13] achieved an impressive 98.43%, showing significant improvement over earlier approaches. In [14], the standalone CNN produced lower accuracy, but when combined with ANN, it reached 97.62%, indicating that hybrid models can enhance performance. In comparison, the proposed CNN model achieved a perfect 100% accuracy, outperforming all referenced studies. This demonstrates that the proposed method not only improves over traditional and hybrid approaches but also achieves the highest possible classification accuracy, making it the most reliable and robust solution among the compared works.

Table 7: Comparison results with related works.

Ref. No.	Accuracy
[8]	89%
[9]	87%
[10]	74%
[11]	81%
[12]	57%
[13]	98.43%
[14]	CNN: 97.62% ANN: 96%
The proposed CNN model	100%

5 CONCLUSIONS

Previous machine learning models, such as Random Forest, SVM, and Decision Trees, battled with overfitting and feature redundancy despite achieving

respectable accuracy levels. We can note that the development of deep learning frameworks such as CNNs has transformed data analysis by making hierarchical pattern detection and automatic feature extraction possible.

In terms of both predicted accuracy and computational efficiency, the suggested CNN-based approach shows a notable improvement over the conventional models that have been in use for the past ten years. This historical development demonstrates how feature selection combined with deep architectures can help close the gap between traditional statistical techniques and contemporary AI-powered solutions.

This study highlighted the effectiveness of the proposed CNN model combined with feature selection techniques in achieving highly accurate and efficient classification results. By applying Mutual Information, Chi-square, and ANOVA with different feature percentages (10%, 30%, 50%), the CNN consistently achieved 100% accuracy, precision, recall, and F1-score, proving its robustness and reliability. While the classification time increased with more features, the performance remained stable, demonstrating the model's efficiency in handling different feature sets. Compared with previous studies, which reported accuracies between 57% and 98.43%, the proposed CNN reached a perfect accuracy level, confirming its superiority. Overall, this research shows that the integration of feature selection with CNN not only ensures maximum accuracy but also improves computational efficiency, offering a powerful solution for future classification tasks.

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Digital Tools for Public Administration of Odesa's Tourism Potential within the UNESCO Heritage Framework

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Abstract: The study examines administrative mechanisms for managing Odesa's tourism potential in the context of its inclusion in the UNESCO World Heritage. Attention is focused on the challenges posed by full-scale war, particularly the damage to cultural monuments, which has significantly impacted the region's tourist attractiveness. Based on a SWOT analysis, the strengths and weaknesses of Odesa's tourism industry, its opportunities and threats, are identified, including: rich architectural heritage, potential for international funding, security risks, and insufficient promotion. A comprehensive approach to managing tourism potential is proposed, comprising six groups of strategies: institutional, regulatory, financial and economic, technological, communication, and environmental. These include the creation of a municipal tourism agency, the development of local regulations based on UNESCO standards, the attraction of grants, the introduction of digital technologies for analysing tourist flows, and the promotion of sustainable tourism. Particular attention is paid to the role of local government bodies, in particular the Department of International Cooperation, Culture and Marketing of the Odessa City Council, as a key player in administering the tourism sector. It is concluded that effective public administration of Odesa's tourism potential should be based on a balance between preserving cultural heritage and developing infrastructure, taking into account the requirements of post-war recovery and Ukraine's integration into the global tourism space.

1 INTRODUCTION

Despite the full-scale invasion by the Russian Federation, the tourism industry has not come to a complete standstill and continues to contribute to the state budget through tax payments. In 2022, some tourism companies even increased their contributions compared to 2021. On average, the tourism industry paid 25.7% less tax to the state budget in the first half of 2022 than in the same period of the previous year. The number of companies decreased by 24.5%, and entrepreneurs by 13.5%. The largest revenues to the state budget were received from tax payments by hotels and sanatorium-resort establishments, which amounted to almost UAH 461 million; however, this amount was 30% lower than in the previous year [1].

Unfortunately, as a result of the Russian Federation's military aggression against Ukraine, not only the logistics, energy and social infrastructure have suffered. Ukraine's cultural and historical heritage, which is an important component of the tourism industry, has also suffered significant losses. As of 25 September 2023, the Odesa region ranked second in terms of the number of cultural heritage sites affected by Russian aggression [2]. The historic centre of Odesa suffered the most, enduring the largest attack by Russian forces since the start of the full-scale invasion of Ukraine during 19–23 July 2023. As a result of the shelling, significant damage was inflicted on UNESCO-protected cultural heritage sites. The Odesa city authorities reported 28 damaged buildings within the protected zone, including the Transfiguration Cathedral [1].

Even now, despite the large-scale invasion of Ukraine by the Russian Federation, Odesa continues to attract the interest of the international community. Therefore, it is important to develop the mechanisms for the public administration of Odesa's tourism potential as a UNESCO historical and cultural heritage site.

2 LITERATURE REVIEW

Recent scholarship demonstrates a growing emphasis on the interconnectedness of heritage protection,

urban governance, and post-conflict recovery processes. International researchers highlight that managing "living heritage" in dynamically transforming cities requires adaptive and resilient administrative approaches. In particular, the works of K. Taylor [3], N. Lanzoni [4], S. Barakat [5], M. Ripp and D. Rodwell [6] analyse how cultural landscapes evolve under social, economic and security pressures, underscoring the challenges inherent in preserving heritage within rapidly changing urban environments. Studies on wartime heritage governance further stress the need for resilience-based planning and the development of tools that enable cultural sites to withstand threats related to armed conflict.

At the same time, research in digital heritage [7], [8], [9] demonstrates the growing effectiveness of GIS systems, drone-based monitoring, and digital-twin technologies for real-time heritage documentation and risk assessment. Parallel studies in tourism governance [10] emphasise crisis communication, managerial flexibility, and coordination among key stakeholders – lessons that are directly applicable to Odesa as a UNESCO site operating under wartime conditions.

An equally important dimension is the system of public administration of the tourism sector in the Odesa region within the context of transformational socioeconomic changes. International experience confirms that the success of tourism sector development depends largely on how the industry is prioritised at the state level and the extent to which it receives systemic governmental support. Since tourism represents a multi-sectoral complex, it requires a higher degree of coordination of economic activities than many other industries. At the same time, excessive state regulation may hinder entrepreneurial initiative, which forms the foundation of competitive market development.

The strengthening of globalisation processes has led to a substantial expansion of tourism's role in shaping transregional connections and disseminating social, political and economic dynamics across borders. For Ukraine, the formation of a positive and recognisable tourist image has become a strategic component of national interests and an important element of international information policy. As a result, tourism has acquired a more pronounced strategic significance, becoming an important factor in the socio-economic progress of the state [11].

These circumstances reinforce the need for effective public administration of tourism, where a clear understanding of the sector's position within the regional and national economy is essential. This approach helps reduce excessive dependence on a sector that is inherently sensitive to external shocks, including economic crises, global disruptions or military conflict [12]. In the current conditions of market development, tourism serves not only as a source of fiscal revenues for local budgets but also as a driver of regional development. At the same time, tourism imposes high ecological requirements on territories, making sustainable environmental management a prerequisite for long-term competitiveness.

Furthermore, tourism is inherently a complex service chain – accommodation, food provision, treatment, entertainment, transportation and other components are interlinked. Because tourists perceive this set of services holistically, the overall impression formed by consumers influences the perceived value of the region as a whole [13]. This highlights the importance of coordinated public administration that supports service quality, protects cultural heritage and ensures the resilience and competitiveness of the tourism sector.

3 RESEARCH GOALS

The study aims to justify and develop effective strategies for public administration of Odesa's tourist potential in the context of its inclusion in the UNESCO World Heritage List. Particular attention is paid to ensuring a balance between the preservation of historical and cultural heritage and the sustainable development of tourist infrastructure in the context of post-war recovery.

To achieve this aim, the following objectives were defined:

- to analyse the current state of the tourism industry in Odesa, taking into account security, economic, and infrastructure challenges;
- to study international and national approaches to cultural heritage management;
- to conduct a SWOT analysis of the tourism potential of the city's historic centre;
- to identify key directions for improving administrative mechanisms for managing Odesa's tourism potential within the UNESCO heritage framework.

4 RESEARCH METHODOLOGY

The methodological basis of the study is a comprehensive interdisciplinary approach that integrates methods of public administration, tourism

economics, cultural heritage studies, and strategic planning. To achieve the research objectives, both qualitative and quantitative analytical techniques were applied.

A central analytical tool used in the study is the parameterised SWOT analysis, which allowed for the systematic identification of strengths, weaknesses, opportunities, and threats related to the tourism potential of Odesa's historic centre, particularly under the external pressures caused by the full-scale invasion of the Russian Federation. The SWOT framework was expanded through specific indicators, including cultural value, infrastructure condition, vulnerability level, and tourism development potential.

To ensure methodological transparency and structure, the study distinguishes several key components:

- Data sources that include UNESCO databases, municipal and regional reports, official tourism statistics, scientific literature, GIS cartographic materials, and documented assessments of damage to cultural heritage sites.
- Analytical tools that encompass parameterised SWOT analysis; comparative analysis with UNESCO-listed port cities; GIS-based mapping and spatial assessment; and content analysis of international heritage governance documents, including UNESCO and ICCROM guidelines.
- Research questions – How has UNESCO inscription reshaped governance priorities in Odesa? Which administrative mechanisms demonstrate the highest effectiveness under wartime conditions? How can cultural heritage preservation be balanced with the development of sustainable tourism during periods of heightened security risks?
- Reasoning steps comprising diagnostic assessment of heritage-tourism interactions; mapping of risks and territorial boundaries of the UNESCO site; evaluation of existing administrative instruments; and synthesis of findings into a multi-mechanism governance model.

In addition to theoretical analysis, the study relies on empirical data, including statistical indicators for the tourism sector, official information from the Odessa City Council, UNESCO documentation, and verified reports on damage to cultural heritage sites. The integration of these methodological tools made it possible to identify key directions for improving public administration mechanisms – specifically institutional, regulatory, financial-economic, technological, communication, and environmental mechanisms – necessary for ensuring the sustainable development of tourism in Odesa as a UNESCO World Heritage site.

.5 RESULTS

Odesa is the administrative centre of the region of the same name in southern Ukraine, located on the Black Sea coast. Due to its strategic location, the city is an important hub for international logistics and the economy. It is a developed infrastructure centre with a powerful port, industry, and significant scientific and cultural potential. The population exceeds 1 million people. Odesa's architecture and urban planning have been shaped by European urban planning traditions and the participation of foreign experts [8].

The historic centre of Odesa is a densely built-up area formed on the site of the former Khadzhibey, designed in the classical style with straight, tree-lined streets and two- and four-storey buildings. Its architecture reflects the city's economic growth in the 19th and early 20th centuries.

The eclectic style of the buildings emphasises Odesa's ethnic and religious diversity, making the city centre a vivid example of intercultural dialogue and multicultural development in 19th-century Eastern European port cities [14].

The full-scale invasion of Ukraine by the Russian Federation has drawn attention to its cultural and historical heritage, and thus to cultural and educational tourism. Constant heavy shelling by the Russian Federation resulted in the damage and destruction of a significant number of cultural heritage sites in Ukraine. As of 26 November 2025, UNESCO verified damage to 512 sites since 24 February 2022 – 152 religious sites, 268 buildings of historical and/or artistic interest, 37 museums, 33 monuments, 18 libraries, 1 archive, and 3 archaeological sites [15].

According to UNESCO, the number of damaged historical and cultural heritage sites by region in Ukraine is as follows: the Kharkiv region – 83; the Odesa region – 63; the Donetsk region – 133; the Kherson region – 35; the Chernihiv region – 22; the Kyiv region – 44; the Zaporizhzhia region – 27; the Lviv region – 15; the Dnipropetrovsk region – 4; the Luhansk region – 47; the Sumy region – 16; the Mykolaiv region – 15; the Vinnytsia region – 3; the Zhytomyr region – 3; the Poltava region – 1 [15].

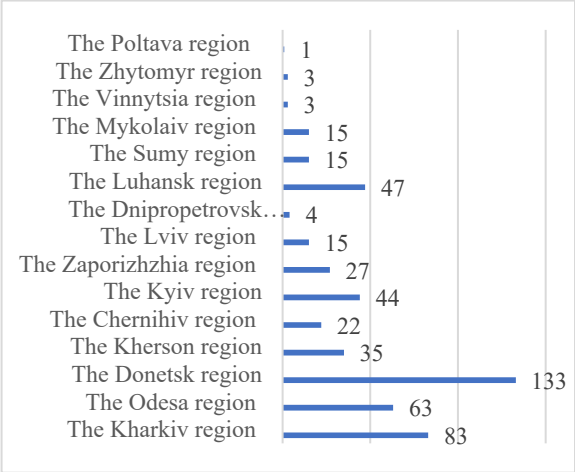


Figure 1: The number of damaged cultural heritage sites by region as a result of russian aggression, as of 26 November 2025.

On 25 January 2023, the historic centre of Odessa was inscribed on the UNESCO World Heritage List [14].

As of 25 January 2023, the area of the nominated site - the historic centre of Odessa – was 237.5 hectares, and the buffer zone covered 1,067.5 hectares. The main territory was delineated by Torgova street, Sadova street, Sviatoslava Karavanskogo (Zhukovskogo) street, Polsky Spusk street, and the adjacent seaport. It included Primorsky Boulevard, Teatralna Square, Deribasivska Street, Gogol Street, parts of Pastera Street, Preobrazhenska Street, Havanna Street, Yevropeiska (Katerynska) Street, Lanzheronivska Street, Nina Strokata (Bunina) Street, Richelievska Street, and Gretska Street. The buffer zone included parts of Balkivska, Staroportofrankovska, Panteleymonivska Streets, and Frantsuzky Boulevard [16].

In April 2024, UNESCO expanded the area of the nominated site of the historic centre of Odesa to 618.54 hectares. The buffer zone covers an area of 618.8 hectares. Currently, the area of the nominated site of the historic centre of Odesa is defined by Staroportofrankovska, Panteleymonivska, Leontovycha, Primorska, Balkivska streets, and Liderosovsky Boulevard. Odesa port is located in the buffer zone of the World Heritage Site [16].

There are 1,354 monuments and cultural heritage sites located within the territory of Odesa, including 42 monuments of national significance. Of these, 1,012 are situated within the boundaries of the Central Historical Area, encompassing 977 sites of architectural, urban planning, and historical heritage at both national and local levels.

An updated inventory list, which also includes newly identified heritage sites, was compiled during the revision of the scientific and project documentation titled ‘Historical and Architectural Reference Plan, Protection Zone Project, and Delimitation of Historical Areas of the City of Odesa’ (2021).

According to the UNESCO World Heritage Committee classification, the historic centre of Odesa is considered a ‘living historic city’– a category that reflects ongoing evolution under the influence of sociocultural and economic transformations. This dynamic nature complicates the assessment of environmental authenticity and the development of effective preservation policies [17].

Let us conduct a SWOT analysis of the tourism potential of Odessa's historic centre.

Table 1: SWOT analysis of the tourism potential of Odesa’s historic centre.

Strengths	Weaknesses
Rich cultural heritage Historical significance Developed infrastructure Cultural events	Infrastructure condition Insufficient marketing Security risks Transportation problems
Opportunities	Threats
International financing Tourist routes Digital marketing Eco-tourism	Military conflicts Economic crises Competition Climate change

A detailed analysis of Table 1 showed that the following were considered strengths: the presence of numerous architectural monuments and cultural complexes of national and international significance; the great importance of the historic centre of Odesa in the context of Ukrainian and European history; well-developed infrastructure in the historic centre of Odesa, including hotels, restaurants and entertainment venues; cultural events held regularly in the historic centre despite the full-scale invasion (festivals, exhibitions and other cultural events), which in turn attracts tourists; the following were identified as weaknesses: the state of infrastructure (some historic buildings are in need of restoration and maintenance); insufficient marketing, i.e. a lack of international advertising and promotion of the tourist opportunities offered by the historic centre of Odesa, even during the full-scale invasion; security risks, i.e. the current military aggression by the Russian Federation may deter potential tourists; transport problems, i.e. the poor quality of roads and public transport, which may make it inconvenient for tourists to comfortably reach the historic centre; the opportunities included: international financing

through grants and investments for the restoration and development of the infrastructure of the historic centre of Odesa; the development of new tourist routes and excursions that highlight the unique aspects of the historic centre and link the history of Odesa with the history of Ukraine and the world; the use of digital technologies to improve the marketing and promotion of tourist products; the introduction of environmental practices in the tourism industry to attract new categories of tourists; threats included: prolonged military aggression by the Russian Federation could seriously affect the security and attractiveness of the Odesa region; global economic problems could reduce the number of tourists (especially foreign tourists) willing to travel; competition, which consists in the fact that other historical centres in Ukraine and neighbouring countries may be more attractive to tourists; environmental problems related to climate change may affect the tourist appeal of Odesa.

This SWOT analysis shows that the historic centre of Odesa has strong tourism potential, which needs to be developed and improved.

The effectiveness of tourism policy is determined not only by managerial decisions at the central level and financial support, but also by the professional activities of local specialists. It is they who adapt the national management model to the regional context. Changes in the structure of specialised departments at the national level often lead to corresponding transformations in regional management mechanisms [18].

Within the framework of decentralisation, tourism policy in Ukraine is implemented through cooperation between public authorities and local self-government bodies at the national, regional and local levels. Regional and district state administrations play a crucial role in regional management. According to the Resolutions of the Cabinet of Ministers of Ukraine [19], [20], they are required to form specialised structural units for tourism and resorts. The type and status of such units are determined by the administration's management under the scope of their functional tasks.

Table 2: Mechanisms for public administration of the Odesa's tourism potential as a UNESCO historical and cultural heritage site.

Mechanism	Indicator
Institutional mechanisms	Involve establishing a clear and coordinated system of interaction between government agencies, public organisations, and private-sector stakeholders. Practical examples include the creation of a joint Odesa – UNESCO Heritage Management Office, the formation of interdepartmental coordination councils, and structured cooperation with NGOs engaged in heritage protection and sustainable tourism development.
Regulatory mechanisms	Ensure the effective development and preservation of Odesa's tourism potential through legally grounded governance tools. These include updated conservation rules, mandatory heritage impact assessments for new interventions, and development restrictions within the buffer zone to ensure compliance with UNESCO requirements
Financial and economic mechanisms	Refer to the mobilisation of financial resources from state, municipal, and international sources to support heritage conservation and tourism development. Relevant instruments include micro-grant programmes for façade restoration, municipal tax incentives, the UNESCO Emergency Heritage Fund, and EU-based funding opportunities such as Creative Europe.
Technological mechanisms	Focus on the integration of innovative digital tools to modernise public administration and enhance the effectiveness of heritage monitoring. These include drone-based mapping of damage, the creation of digital twins of historic areas, QR-coded tourist navigation systems, and the use of artificial intelligence for monitoring structural stability.
Communication mechanisms	Relate to the formation of an effective communication strategy between authorities, businesses, local communities, and international audiences. Important measures include wartime tourism safety protocols, multilingual crisis communication systems, and global awareness campaigns that highlight Odesa's resilience and cultural value.
Environmental (ecological) mechanisms	Aim to minimise the negative impact of tourism on cultural heritage and the urban environment. Priority measures include climate-risk monitoring, sustainable waste management practices, the introduction of energy-efficient solutions, and the development of heat-mitigating public spaces in the historic centre.

The structure of tourism administration in the Odessa region is represented, in particular, by the Department of International Cooperation, Culture and Marketing of the Odessa City Council (14, Yevropeiska Street). This executive body was established in accordance with the Law of Ukraine 'On Local Self-Government' [21] as the successor to several specialised structures, in particular the departments of culture, tourism, international cooperation and cultural heritage administration [22]-[25].

In its activities, the Department is guided by the Constitution of Ukraine, current legislation and regulations of local self-government bodies.

The Department has the following management structure: Department of Culture, Department of Tourism, Department of International Relations, Department for Cooperation with UNESCO and Cultural Heritage Protection [26].

The Department of International Cooperation, Culture and Marketing of the Odessa City Council, as a public authority, plays a crucial role in preserving the city's historical heritage.

The results of the study enabled the identification of key administrative mechanisms necessary for strengthening the management of Odesa's tourism potential as a UNESCO World Heritage site. These mechanisms are structured into six interconnected groups – institutional, regulatory, financial-economic, technological, communication, and environmental – each with specific indicators and practical applications relevant to wartime and post-war urban governance.(Table 2):

The combination of these mechanisms provides a comprehensive framework for improving public administration in the tourism sector. Their coordinated implementation will contribute to the preservation of Odesa's cultural heritage, the enhancement of its international visibility, and the sustainable development of tourism during wartime and throughout the post-war recovery period.

Thus, public management of Odesa's tourism potential as a UNESCO historical and cultural heritage site requires a comprehensive approach that combines institutional, regulatory, financial, technological, communication and environmental mechanisms. The implementation of these mechanisms will ensure the sustainable development of tourism, contribute to the preservation of historical and cultural heritage, enhance the city's international image and shape a competitive tourism strategy.

6 CONCLUSIONS

Odesa, as one of the leading tourist centres of the Black Sea region, possesses a favourable geographical location, a well-developed infrastructure, and a rich cultural heritage, further underscored by the inscription of its historic centre on the UNESCO World Heritage List. Nevertheless, the full-scale war has resulted in the destruction and damage of numerous cultural heritage sites, significantly undermining the city's tourism potential. The SWOT analysis carried out in this study confirms Odesa's considerable strengths - most notably its architectural landmarks and opportunities for attracting international funding for restoration and development. At the same time, the analysis highlights critical challenges such as infrastructure deterioration, insufficient marketing, persistent security risks, and transport difficulties, all of which constrain the city's ability to fully realise its tourism potential.

The findings of the research demonstrate that the sustainable development of Ukraine's tourism sector requires targeted investments in infrastructure modernisation, the strengthening of international partnerships, and the implementation of an effective marketing strategy to promote Odesa as a resilient cultural destination. These efforts must be supported by a governance framework that balances heritage preservation with contemporary tourism needs.

The conclusions of the study can be summarised as follows:

1) Odesa's UNESCO inscription confirms its global cultural value**,** yet wartime destruction exposes significant vulnerabilities that require urgent protective and recovery measures.
2) Municipal administrative capacity remains substantial**,** but stronger coordination, clearer institutional mandates, and deeper integration with UNESCO's governance instruments are needed to enhance effectiveness.
3) SWOT analysis reveals a strong heritage base and opportunities for international support, while also identifying key constraints, including infrastructure decline, weak promotion, and elevated security concerns.
4) The six-mechanism governance framework proposed in the study **-** institutional, regulatory, financial-economic, technological, communication, and environmental - offers a holistic foundation for aligning cultural heritage preservation with sustainable tourism development.

5) Research limitations include reliance on secondary data sources and restricted access to field-based assessments due to wartime conditions, which may affect the generalisability of findings.
6) Future research directions should explore the development of inclusive tourism products, the expansion of digital monitoring tools for heritage protection, and the modelling of post-war investment scenarios that could accelerate Odesa's cultural and tourism recovery.

In particular, additional analysis is required to formulate public administration strategies for inclusive tourism, ensuring that people with disabilities have full access to the historic centre of Odesa and its cultural assets.

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Fractional Diffusion and Lévy Processes for Financial Derivative Pricing

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Keywords: Fractional Diffusion Equation, Fractional Brownian Motion (fBm), Heston Model, Lévy -Driven Stochastic Volatility Model.

Abstract: This paper develops a joint framework for the fractional diffusion equation driven by Lévy processes within a stochastic volatility setting, serving as an extension of the classical Heston model. We present the mathematical foundations of the model, emphasizing the dynamics of asset prices influenced simultaneously by fractional Brownian motion, which introduces long memory, and Lévy processes, which capture discontinuous jumps. The integration of these components allows the model to account for both fat-tailed and skewed return distributions. A Fourier transform representation is derived for option pricing under this generalized framework, and a Monte Carlo simulation scheme is proposed to numerically evaluate the associated stochastic integrals. Furthermore, maximum likelihood estimation (MLE) is employed for parameter estimation, and a systematic procedure for applying the proposed model to empirical financial data is outlined. The results demonstrate that the model provides a more realistic representation of market dynamics than classical approaches, particularly in explaining volatility clustering, extreme events, and the heavy-tailed nature of financial returns. Overall, the fractional diffusion–Lévy process framework offers a robust alternative for both theoretical research and practical applications in financial modeling.

1 INTRODUCTION

In recent decades, the modeling of financial markets has moved far beyond classical approaches such as the Black–Scholes framework. While these traditional models provided a foundation for option pricing and risk management, they often fail to capture crucial empirical features of asset returns, including volatility clustering, heavy tails, and sudden jumps. Among the more advanced models, the Heston stochastic volatility model has become widely used because it allows volatility itself to evolve as a random process rather than a fixed parameter.

Despite its popularity, the Heston model is built on standard Brownian motion. This assumption limits its ability to reflect the complex behavior observed in financial time series. In particular, empirical evidence shows that financial returns exhibit long-range dependence and persistent deviations from normality, features that cannot be adequately explained by Gaussian dynamics alone. These limitations have encouraged researchers to seek more flexible processes to drive asset prices [1].

Two promising directions have emerged. The first is fractional Brownian motion, which introduces a memory effect through the Hurst parameter, allowing the model to capture persistent or anti-persistent structures in returns. The second is the use of Lévy processes, which incorporate discontinuous jumps and are therefore able to reproduce extreme market events. Each approach adds realism, but combining them within a unified framework can provide a more comprehensive description of asset dynamics [1], [2].

The purpose of this paper is to extend the Heston model by embedding it within a fractional diffusion framework enriched by Lévy jumps. In doing so, we aim to build a model capable of reflecting both continuous price variations and sudden shocks, while maintaining mathematical tractability for applications in derivative pricing and risk management. We derive the theoretical formulation of the model, establish its option pricing representation through Fourier techniques, and implement Monte Carlo simulations to explore its numerical properties. Furthermore, we investigate parameter estimation using maximum likelihood methods and demonstrate applications to

real financial data, including the S\&P 500 index and the iShares Europe ETF [2].

This integration of fractional and jump dynamics represents a step toward more realistic financial modeling. By addressing both long memory and discontinuities, the proposed model has the potential to improve the accuracy of option valuation and the measurement of market risk.

Classical models in financial economics, such as the Black–Scholes framework, assume normally distributed returns and constant volatility. While elegant, these assumptions prevent the model from explaining well-documented empirical phenomena such as volatility clustering, heavy tails, and sudden jumps in asset prices. To overcome these shortcomings, Heston (1993) [2] introduced a stochastic volatility model in which the variance follows a mean-reverting process. This provided a more realistic description of option pricing and helped explain the volatility smile observed in practice.

Later extensions incorporated jump components to capture abrupt market shocks. Notable examples include the Merton jump-diffusion model and the Variance Gamma process, both of which improved the ability to model heavy-tailed and asymmetric return distributions. However, these models still lack the capacity to represent long-memory effects, which are frequently observed in high-frequency financial data.

To address persistence and long-range dependence, researchers turned to fractional Brownian motion (fBm), which incorporates memory through the Hurst exponent. At the same time, Lévy processes have gained popularity as they can jointly capture continuous price fluctuations and discontinuous jumps [3], [4].

In recent years, efforts have been made to integrate these two perspectives. For example, Aljethi (2022) developed a fractional Lévy framework for option pricing, supported by numerical sensitivity analysis. More recently, new studies derived fractional differential equations based on Lévy processes to better align theoretical models with empirical data (see Science Direct, 2023). A comprehensive survey published in 2024 highlights the advances of fractional Black–Scholes equations, emphasizing their ability to capture extreme events and nonlinear volatility patterns, along with analytical and numerical solution techniques (MDPI, 2024).

Nevertheless, despite this progress, a fully unified framework that systematically integrates fractional diffusion dynamics with Lévy-driven jumps for practical applications in option pricing and risk management is still underdeveloped.

The contribution of this paper lies in bridging this gap. We propose a generalized extension of the Heston model that integrates fractional Brownian motion with Lévy jumps into a single coherent diffusion framework. The approach provides a Fourier-based option pricing representation, a Monte Carlo simulation scheme, and a maximum likelihood estimation strategy for parameter calibration. Taken together, these innovations offer both theoretical novelty and empirical applicability.

2 MATHEMATICAL FORMULATION

The Heston model is described by the following system of stochastic differential equations (SDEs). The stock price S_t follows the SDE [2], [5]:

$$dS_t = \mu s_t dt + \sqrt{V_t} S_t dW_t^H. \quad (1)$$

Where μ: The drift rate of the stock price, V_t: The instantaneous variance (volatility squared) and W_t^H: A fractional Brownian motion for the stock.

And the variance V_t follows the SDE [5]:

$$dV_t = \theta(\mu_v - V_t)dt + \sigma_v \sqrt{V_t} dW_t^V. \quad (2)$$

Where θ is the rate of mean reversion, μ_v is the long-term mean level of volatility and σ_v is the volatility of volatility. The two Wiener processes W_t^H and W_t^V are correlated with a correlation coefficient ρ.

$$dW_t^H \, dW_t^V = \rho dt.$$

The variance process (2) was originally used by Cox, Ingersoll, and Ross (1985) for modeling the short term interest rate. It is defined by three parameters: θ, σ^2, and γ. In the context of stochastic volatility models they can be interpreted as the long term variance, the rate of mean reversion to the long term variance, and the volatility of variance, respectively, if we assume that the Wiener process in the Heston model is replaced by a Lévy process, the model can be generalized to incorporate jumps in addition to the continuous price movements. This leads to a more complex framework known as a Lévy-driven stochastic volatility model. We have the model:

When we introduce a Lévy process L_t to account for jumps, the stock price dynamics become [6]:

$$dS_t = \mu s_t dt + \sqrt{V_t} S_t dW_t^H + S_t dL_t. \quad (3)$$

Where dL_t: Represents the jump component of the stock price, modeled by a Lévy process, and the variance dynamics remain the same as in the original Heston model (2), where W_t^V can still be correlated with the Lévy process.

The empirical evidence suggests that the tail of the risk-neutral return distribution exhibits "fat" characteristics as maturity increases, traditionally interpreted as slow convergence to normality. This phenomenon has been attributed to persistent stochastic volatility processes. However, this modeling approach proposes an alternative perspective, positing that the observed data may indicate a violation of the conditions necessary for the central limit theorem, leading to a risk-neutral distribution that does not converge to normality [7], [8].

To explain the fat tails in the return distribution, the model introduces a parameter αα, which controls tail thickness relative to the central mass. In the Black-Scholes model, Brownian motion represents a special case of the αα-stable class with $\alpha = 2$. To generate fat tails, α must be less than 2, but this results in infinite variance for log returns, raising concerns about the existence of a martingale measure and the finiteness of option values [7], [9].

To address this issue, the model incorporates a second parameter, β, which ranges from -1 to 1, governing the skewness of the distribution. The key innovation is focusing on the case where $\beta = -1$, inducing maximum negative skewness in the Lévy α-stable motion. Under this condition, it is proven that all conditional moments for the index level exist, despite the log return having infinite variance. This specification effectively captures the highly skewed nature of the implied density for log returns, a characteristic that neither Brownian motion nor symmetric Lévy αα-stable motion can adequately represent [10].

The standardized Lévy αα-stable motion, denoted as $L(\alpha, \beta)$, is martingale and serves as a potential driver for the risk-neutral process of discounted index levels. As a Lévy process, it possesses independent and stationary increments, with the increment $dL(\alpha, \beta)$ following an αα-stable distribution characterized by zero drift, a dispersion of $dt(1/\alpha)$, and a skew parameter β. The fractional Brownian motion unlike standard Brownian motion, its characterized by Hurst parameter H, which influences the correlation structure of the increments.

For $H \in (0,1)$ [1], [3]:

- if $H = 0.5$, it reduces to standard Brownian motion;
- if $H > 0.5$, the process exhibits persistent behavior (long-rang dependence);
- if $H < 0.5$, it exhibits anti-persistent behavior.

3 LÉVY PROCESS

A Lévy process has independent and stationary increments, allowing for both continuous changes (like Brownian motion) and discrete jumps. The characteristics of the Lévy process can be defined by its characteristic function or Lévy-Khintchine representation [11], [12]:

$$\phi(u,t) = E\left[e^{iuL_t}\right] = \exp\left(i\delta u + \int e^{iux} - 1 - iux.1_{|x|<1}vdx\right), \quad (4)$$

where δ: Drift term of the Lévy process and vdx: Lévy measure, which describes the jump intensity and distribution. In a risk-neutral framework, replace μ with the risk-free rate r. However, if we consider instead of fractional Brownian motion, we need to adjust our understanding of the stochastic calculus involved. To derive the solution for S_t, we can use the Ito formula adapted for fractional Brownian motion, the stochastic differential equation (SDE) (3) [13].

$$dS_t = \mu s_t dt + \sqrt{V_t} S_t dW_t^H + S_t dL_t.$$

To solve this equation, we can use Itos formula for a function $f(t, S_t)$, for some function f, then [13]-[15]:

$$df(t,S_t) = \left(\frac{\partial f}{\partial t} + \frac{\partial f}{\partial x}\mu S_t + \frac{1}{2}\frac{\partial^2 f}{\partial x^2}\sigma^2 S_t^2 + jump\ terms\right)dt + \frac{\partial f}{\partial x}\sigma S_t dW_t + \frac{\partial f}{\partial x} S_t dL_t. \quad (5)$$

In our case. Let's define $f(t, S_t) = \log S_t$. Thus, we can express S_t in terms of $f(t, S_t)$.

We have, $\frac{\partial f}{\partial t} = 0$ (since f does not explicitly depend on t), $\frac{\partial f}{\partial x} = \frac{1}{S_t}$, and $\frac{\partial^2 f}{\partial x^2} = \frac{1}{S_t^2}$.

Substituting these derivatives into the Fractional Ito formula gives

$$df(t,S_t) = \left(\mu - \frac{1}{2}V_t\right)dt + \sqrt{V_t}dW_t^H + dL_t. \quad (6)$$

Integrating both sides from 0 to t:

$$\log S_t - \log S_0 = \int_0^t \left(\mu - \frac{1}{2}V_s\right)ds + \int_0^t \sqrt{V_s}dW_s^H + \int_0^t dL_s,$$

$$\log S_t = \log S_0 + \int_0^t \left(\mu - \frac{1}{2}V_t\right) ds + \int_0^t \sqrt{V_s} dW_s^H + \int_0^t dL_s.$$

Exponentiating both sides yields

$$S_t = S_0 \exp\left(\int_0^t \left(\mu - \frac{1}{2}V_s\right) ds + \int_0^t \sqrt{V_s} dW_s^H + \int_0^t dL_s\right),$$

$$S_t = S_0 \exp\left(\mu t - \frac{1}{2}\int_0^t V_s\, ds + \int_0^t \sqrt{V_s} dW_s^H + L_t\right), \quad (7)$$

To solve the integral $\int_0^t \sqrt{V_s} dW_s^H$, using numerical methods such as Monte Carlo simulations.

3.1 Define the Simulation Parameters

To perform the numerical simulation of the proposed fractional diffusion–Lévy model, the following key parameters are defined:

- Time Interval: $[0, t]$;
- Number of Simulations: $N\ (e.g., 10{,}000)$;
- Time Steps: $M\ (e.g., 100)$;
- Hurst Parameter: $H\ (e.g., 0.7)$;
- Final Time: $t\ (e.g., 1.0)$;
- Numerical Simulation.

3.1.1 Discretization of Time

The time interval is discretized into Msteps:

$$\Delta t = \frac{t}{M}.$$

Let $t_k = k \cdot \Delta t \ \ for\ k = 0,1, \ldots, M.$

3.1.2 Simulating Fractional Brownian Motion

Fractional Brownian motion is generated using Cholesky decomposition of the covariance matrix, ensuring the correct correlation structure of the increments.

3.1.3 Simulating V_s

The variance V_t may be assumed deterministic ($V_t = \sigma^2$) or simulated as a stochastic process. For example, it can follow a geometric Brownian motion or the Heston stochastic variance dynamics.

3.2 Monte Carlo Simulation Algorithm

The stochastic integral $\int_0^t \sqrt{V_s}\, dW_s^H$ is approximated numerically using the trapezoidal rule. Monte Carlo simulations are conducted with $N = 10{,}000$ repetitions, each discretized into $M = 100$ time steps. The mean and variance of the simulated integrals are then computed to obtain statistical properties of the process.

4 ESTIMATE THE PARAMETERS OF THE HESTON MODEL

To estimate the parameters of the Heston model with fractional Brownian motion using Quasi-Maximum Likelihood Estimation (QMLE), the Table 1 shows the estimated parameters of the model, the QMLE, also known as pseudo-maximum likelihood estimation, is a statistical technique employed to estimate model parameters when the true likelihood function is either unknown or computationally intractable. Rather than maximizing the true likelihood function, QMLE optimizes a "quasi-likelihood" function, which is constructed under the assumption of a specific distribution that may differ from the actual data-generating process. Despite the potential divergence between the assumed and true distributions, QMLE frequently produces parameter estimates that are consistent and asymptotically efficient under certain regularity conditions. The method relies on an assumed likelihood function based on a given distribution (e.g., normal or Gaussian), even when the true underlying distribution of the data does not conform to this assumption. Consistency of the parameter estimates is maintained provided the quasi-likelihood accurately captures the mean and variance structure of the data. Furthermore, QMLE achieves asymptotic efficiency if the quasi-likelihood coincides with the true likelihood; otherwise, efficiency may be diminished, though consistency remains intact under mild assumptions. QMLE is extensively applied in econometrics, time series analysis, and generalized linear models, particularly in scenarios where the true error distribution is unknown or complex. Its ability to yield reliable estimates despite distributional misspecification makes it a valuable tool in statistical modeling and inference, we will follow a systematic approach [16], [17]. This includes defining the model, deriving the likelihood function, and then estimating the parameters. To apply QMLE, we need to discretize the model. Assume we observe S_t at discrete time $t_0, t_1, \ldots, t_n$. We define the time increments as $\Delta t = t_{i+1} - t_i$, the discretized stock price can be approximated as

$$S_{t_{i+1}} = S_{t_i}\left(1 + \mu\Delta t + \sqrt{V_t}\,\Delta W_{t_i}^H + \Delta L_{t_i}\right). \quad (8)$$

Where $\Delta W_{t_i}^H$ is the increment of fractional Brownian motion And variance.

$$V_{t_{i+1}} = V_{t_i} + \theta\left(\mu_V - V_{t_i}\right)\Delta t + \sigma_V\sqrt{V_{t_i}}\Delta W_i. \quad (9)$$

The MLE is constructed based on the joint distribution of observed data, we can express the log-likelihood as follows. [27] The log returns can be computed as

$$\begin{aligned} R_t &= \log S_t - \log S_{t-1} = \log\frac{S_{t_{i+1}}}{S_{t_i}} \\ &= \left(\mu - \frac{1}{2}V_t\right)dt + \sqrt{V}_t\, W_i^H + dL_t. \end{aligned} \quad (10)$$

Assuming the increments of R_t are approximately normality distributed, the log-likelihood function L can be expressed as:

$$L\,(\mu, \theta, \mu_V, \sigma_V|R) = \sum_{i=0}^{n-1} f(\,R_t|\,\mu, V_{t_i}), \quad (11)$$

where $f(R_i|\mu, V_{t_i})$ is the probability density function of the log-normal distribution, we will take the log-likelihood function becomes [17], [18]:

$$\ell\,(\mu, \theta, \mu_V, \sigma_V|R) = \sum_{i=0}^{n-1}\left[-\frac{1}{2}\log\left(2\pi\hat{V}_t\right) - \frac{(\,R_t - \mu)^2}{2\hat{V}_t}\right], \quad (12)$$

where $\hat{V}_t$ is the estimated volatility at time t. To estimate $\hat{V}_t$, we can use realized volatility which is computed from the observed return.

$$\hat{V}_t = \frac{1}{\Delta t}\sum_{i=1}^{k}(R_{t-i} - \bar{R})^2. \quad (13)$$

Where, Δt is time interval and $\bar{R}$ its mean return over the interval. For fractional Brownian motion, the volatility can be modeled as:

$$\hat{V}_t = V_0 e^{\theta t + \sigma W_t^H}. \quad (14)$$

To find the parameters estimates, maximize log-likelihood function with respect to the parameters $\mu, \theta, \mu_v, \sigma_v$:

$$\left(\hat{\mu}, \hat{\theta}, \hat{\mu}_v, \hat{\sigma}_v\right) = \arg max_{\mu,\theta,\mu_v,\sigma_v} L(\,\mu, \theta, \mu_v, \sigma_v\,). \quad (15)$$

This maximization can be performed using numerical optimization techniques. We will use the Newton-Raphson method. To apply the Newton-Raphson method we will the gradient of the log-likelihood function with respect to each parameter

$$\frac{\partial L}{\partial \mu} = \sum_{t=1}^{n}\frac{(R_t - \mu)}{\hat{V}_t}. \quad (16)$$

And derivative with respect to θ we need requires differentiating with respect to the estimated volatility, which itself is a function of θ. Assuming $\hat{V}_t$ depends on θ

$$\frac{\partial L}{\partial \theta} = \sum_{t=1}^{n}\left[-\frac{1}{2}\frac{\partial \hat{V}_t}{\partial \theta} - \frac{(R_t - \mu)}{2\hat{V}_t^2}\frac{\partial \hat{V}_t}{\partial \theta}\right], \quad (17)$$

μ_V and σ_v. These derivatives will also depend on the specific formulation of $\hat{V}_t$. Now, we calculate the Hessian matrix consists of the second derivatives of the log-likelihood function [19], [18]:

$$H = \begin{bmatrix} \frac{\partial^2 L}{\partial \mu^2} & \frac{\partial^2 L}{\partial \mu \partial \theta} & \frac{\partial^2 L}{\partial \mu \partial \mu_v} & \frac{\partial^2 L}{\partial \mu \partial \sigma_v} \\ \frac{\partial^2 L}{\partial \theta \partial \mu} & \frac{\partial^2 L}{\partial \theta^2} & \frac{\partial^2 L}{\partial \theta \partial \mu_v} & \frac{\partial^2 L}{\partial \theta \partial \sigma_v} \\ \frac{\partial^2 L}{\partial \mu_v \partial \mu} & \frac{\partial^2 L}{\partial \mu_v \partial \theta} & \frac{\partial^2 L}{\partial \mu_v^2} & \frac{\partial^2 L}{\partial \mu_v \partial \sigma_v} \\ \frac{\partial^2 L}{\partial \sigma_v \partial \mu} & \frac{\partial^2 L}{\partial \sigma_v \partial \theta} & \frac{\partial^2 L}{\partial \sigma_v \partial \mu_v} & \frac{\partial^2 L}{\partial \sigma_v^2} \end{bmatrix}.$$

Thin we update parameters using Newton-Raphson method (N-R), the N-R update rule is given by

$$\theta^{(k+1)} = \theta^{(k)} - H^{-1}\nabla L\left(\theta^{(k)}\right). \quad (18)$$

Where, $\theta^{(k)}$ is the parameter vector at iteration k, ∇L is the gradient vector and H^{-1} is the inverse of the Hessian matrix, we can write the iterative algorithm.

1) Initialize: set initial guesses for $\mu, \theta, \mu_v, \sigma_v$.
2) Compute log-likelihood: calculate $L\,(\mu, \theta, \mu_v, \sigma_v)$
3) Calculate Gradient and Hessian: compute the gradient and Hessian matrix.
4) Update parameters: use the newton-Raphson update rule.
5) Check Convergence: if the change in parameters is below a certain threshold, stop; otherwise, return to step 2.

Given the parameters, we can analyze the conditional moments of the returns. For the Lévy process with $\alpha < 2$ and $\beta = -1$, the moments can be expressed as follows [20], [21], [17]:

$$E[R_t|F_{t-1}] = \mu + \theta(\mu_v - V_{t-1}).$$

and

$$Var(R_t|F_{t-1}) = V_{t-1}.$$

The parameters were estimated using S&P 500 index data using the maximum likelihood method for

the period from 1/1/2007 to 12/31/2013 and the results are as shown below:

Table 1: Represents the values of the parameters estimating using the QMLE method.

Parameters	Sample size (n)
	n=1000
μ	-0.09308951
θ	0.09999268
μ_v	0.20022537
σ_v	0.1000030

The parameter μ represents the drift term in the returns equation, which captures the average growth or decline rate of the asset's log returns over time. A negative value ($\mu = -0.09308951$) suggests that the returns exhibit a downward trend on average, indicating that the asset has a negative expected return over the sample period. This could reflect a bearish market trend dataset where the returns are biased downward, this result is based on real data (S&P500), it might indicate a period of market decline or other structural factors affecting in the returns. The parameter θ represents the speed at which the variance (V) reverts to its long-term mean (μ_v). A value of $\theta = 0.09999268$ indicates that the variance tends to revert to its equilibrium level $\mu_v = 0.20022537$ at a moderate rate, the mean reversion speed is relatively low ($\theta \approx 0.1$), meaning that the variance process is persistent and takes time to return to its long-term mean deviations. This is consistent with the behavior of volatility in financial markets, where high volatility tends to persist for extended periods before reverting to normal levels. The parameter μ_v represents the long-term average level of variance (V), a value of $\mu_v = 0.20022537$ suggests the variance fluctuates around this level over the long run. This value is reasonable for financial data, as it reflects a moderate level of variance, which is typical for daily returns in equity markets. In the context of the S&P500, this indicates that the typical daily variance of returns is around 0.2, which corresponds to standard deviation of approximately $\sqrt{0.2} \approx o.447$ or 44.7%. the parameter σ_v represents the volatility of the variance process, which measures how much the variance (V) fluctuates over time, a value of $\sigma_v = 0.100003$ suggests that the variance process is sufficiently stochastic fluctuations. This value indicates that the variance process is sufficiently stochastic, meaning that variance (V) is not constant but fluctuates over time due to random shocks, the volatility of variance (σ_v) is crucial for capturing realistic market dynamics, as it reflects the variability of volatility itself, which is often observed in financial markets. The results demonstrate that the stochastic volatility model provides a reasonable representation of the dynamics of returns and variance for the given sample size $(n = 1000)$. The estimated parameters $(\mu, \theta, \mu_v, \sigma_v)$are consistent with theoretical expectations and provide insights into the behavior of financial data, particularly the S&P 500 index.

5 THE FRACTIONAL DIFFUSION EQUATION WITH LÉVY PROCESS

The core fractional diffusion equation for the modified Heston model can be expressed as [6], [21], [22], [23]:

$$\frac{\partial^\beta V}{\partial t^\beta} = D\,\frac{\partial^\alpha V}{\partial x^\alpha} - rV + L_t, \quad (19)$$

Where V is option price or value of the underlying asset, D is diffusion coefficient, $\frac{\partial^\beta V}{\partial t^\beta}$ is fractional time derivative of order β, $\frac{\partial^\alpha V}{\partial x^\alpha}$ is fractional spatial derivative of order α, r is Risk-free interest rate and L_t is the jump term modeled as Lévy process [3], [30], [31], to solve this equation we will use the Fourier transform of a function $V(x,t)$ is defined as:

$$\hat{V}(k,t) = F\{V(x,,t)\} = \int_{-\infty}^{\infty} V(x,t)\, e^{-ikx} dx, \quad (20)$$

and the inverse Fourier transform is given by:

$$V(x,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \hat{V}(k,t)\, e^{-kx} dk. \quad (21)$$

Applying the Fourier transform to both sides of the fractional diffusion equation gives [8], [24], [25]:

$$F\left\{\frac{\partial^\beta V(x,t)}{\partial t^\beta}\right\} = D\,F\left\{\frac{\partial^\alpha V(x,t)}{\partial x^\alpha}\right\} - r\,F\{V(x,,t)\} + F\{L_t\},$$

by using the properties of the Fourier transform, we have. Using the fractional derivative in the Fourier domain, we get

$$F\left\{\frac{\partial^\beta V(x,t)}{\partial t^\beta}\right\} = (iw)^\beta \hat{V}(k,,t),$$

where w is the frequency variable in the time domain

$$F\left\{\frac{\partial^\alpha V(x,t)}{\partial x^\alpha}\right\} = (ik)^\alpha \hat{V}(k,,t).$$

Substituting these transforms into the fractional diffusion equation yields:

$$(iw)^{\beta}\hat{V}(k,,t) = D\,(ik)^{\alpha}\hat{V}(k,,t) - r\hat{V}(k,,t) + \hat{L}_t. \quad (22)$$

Rearranging the equation gives.

$$\hat{V}(k,,t)\left(\,(iw)^{\beta} - D\,(ik)^{\alpha}\,\right) + r\hat{V}(k,,t) = \hat{L}_t.$$

$$\hat{V}(k,,t) = \frac{\hat{L}_t}{(\,(iw)^{\beta} - D\,(ik)^{\alpha}\,) + r}. \quad (23)$$

We have L_t is a Lévy process, its Fourier transform can be expressed as

$$\hat{L}_t = \emptyset L_t = \int_{-\infty}^{\infty} L_t\, e^{-iwt} dt,$$

to solve this equation, we can use the characteristic function of a Lévy process, which is given by

$$\emptyset L_t = e^{\int_0^t \Psi(w) ds},$$

where $\Psi(w)$ is the characteristic exponent of the Lévy process (Lévy-Khintchine formula) [31], [32]:

$$\Psi(w) = i\mu w - \frac{1}{2}\sigma^2 w^2 + \int_{-\infty}^{\infty} e^{iwx} - 1 - iwx1_{|x|<1}\, vdx, \quad (24)$$

where μ is drift parameter, $\sigma^2$is the diffusion parameter, and vdx is the Lévy measure.

Substituting the characteristic exponent into the Fourier transform expression, we get [4], [26]:

$$\hat{L}_t = \emptyset L_t = e^{\int_0^t \Psi(w) ds} = e^{t\Psi(w)}. \quad (25)$$

Now, to find the final solution of $V(x,t)$, we need to take the inverse Fourier transform

$$V(x,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{e^{t\Psi(w)}}{(\,(iw)^{\beta} - D\,(ik)^{\alpha}\,) + r}\, e^{ikx} dk.$$

The poles of the integrand are the solutions to the

$$\left(\,(iw)^{\beta} - D\,(ik)^{\alpha}\,\right) + r = 0,$$

let's denote the solutions as $z_1, z_2, \ldots, z_n$. These will be the poles of the integrand, the residue of the integrand at poles z_k is given by [27]:

$$Res\frac{e^{t\Psi(w)}}{(\,(iw)^{\beta} - D\,(ik)^{\alpha}\,) + r}, z_k = \lim_{w \to z_k} \frac{e^{t\Psi(w)}}{(\,(iw)^{\beta} - D\,(ik)^{\alpha}\,) + r}.$$

To compute the residue, we need to evaluate the limit and the derivative of the numerator and denominator at the poles z_k

The derivative of the numerator is

$$\frac{d}{dw} e^{t\Psi(w)} = t\, e^{t\Psi(w)}\, \Psi'(w).$$

The derivative of the denominator is

$$\frac{d}{dw}\left[\left(\,(iw)^{\beta} - D\,(ik)^{\alpha}\,\right) + r\right] = i^{\beta}\beta(iw)^{\beta-1} - iD^{\alpha}k^{\alpha}(ik)^{\alpha-1}.$$

Then, we substituting these derivatives into residue formula, we get [28], [29]:

$$Res\frac{e^{t\Psi(w)}}{(\,(iw)^{\beta} - D\,(ik)^{\alpha}\,) + r}, z_k = \frac{t\, e^{t\Psi(z_k)}\, \Psi'(z_k)}{i^{\beta}\beta z_k^{\beta-1} - iD^{\alpha}k^{\alpha}(iz_k)^{\alpha-1}}.$$

By using the residue theorem, we have

$$V(x,t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{e^{t\Psi(w)}}{(\,(iw)^{\beta} - D\,(ik)^{\alpha}\,) + r}\, e^{ikx} dk$$

$$= 2\pi \sum_{k=1}^{n} Res\frac{e^{t\Psi(w)}}{(\,(iw)^{\beta} - D\,(ik)^{\alpha}\,) + r}, z_k\, e^{ikx},$$

$$V(x,t) = 2\pi \sum_{k-1}^{n} \frac{t\, e^{t\Psi(z_k)}\, \Psi'(z_k)}{i^{\beta}\beta z_k^{\beta-1} - iD^{\alpha}k^{\alpha}(iz_k)^{\alpha-1}} e^{ikx}. \quad (26)$$

The final solution for $V(x,t)$ is expressed in terms of the residues and the pole locations $z_1, z_2, \ldots, z_n$, which depend on the model parameters μ, σ^2, the Lévy measure $\nu(dx)$, the diffusion coefficient D, the risk-free rate r, and the orders of the fractional derivatives α and β. To further simplify the solution, we can express the residues in terms of the model parameters. This may involve solving the equation $\left(\,(iw)^{\beta} - D\,(ik)^{\alpha}\,\right) + r = 0$ to find the pole locations z_k, and then evaluating the residue formula at these points.

6 APPLICATION OF FRACTIONAL DIFFUSION EQUATION WITH LÉVY PROCESSES TO S&P 500 AND ISHARES EUROPE ETF (IEV)

The application of the fractional diffusion equation with Lévy processes to financial markets such as the S&P 500 and iShares Europe ETF (IEV) involves extending classical financial models (like the Heston model) to better represent real-world market behaviors. Detailed insights into the concepts, methodology, and simulations discussed in the paper.

6.1 Fractional Diffusion Equation with Lévy Processes

The classical Heston model employs stochastic volatility driven by Brownian motion, assuming continuous price movements. However, this approach

is limited in its ability to capture several important features of real financial markets, including volatility clustering, fat tails, and sudden jumps.

Volatility clustering refers to alternating periods of high and low volatility, while fat tails describe the presence of extreme movements in asset returns. In addition, financial markets often exhibit jumps, which correspond to abrupt price changes caused by macroeconomic events or unexpected news.

To address these limitations, the fractional diffusion equation with Lévy processes extends the classical framework in two key ways. First, it incorporates fractional Brownian motion to model long-range dependencies and memory effects in price dynamics. Second, it introduces Lévy processes to capture discontinuities, skewness, and heavy-tailed behavior in return distributions.

6.2 Application to Financial Markets

6.2.1 S&P 500 Market Dynamics

The S&P 500, a benchmark index for U.S. equities, exhibits several well-known stylized facts of financial markets, including high liquidity, volatility clustering, fat-tailed return distributions, and sudden price jumps driven by macroeconomic events.

Volatility clustering is reflected in alternating periods of high and low volatility, while fat tails indicate the presence of extreme return values. In addition, jumps represent abrupt and significant price changes caused by unexpected news or economic shocks.

These characteristics are illustrated in Figure 1, which demonstrates fat tails in the return distribution, skewness capturing asymmetry in price movements, and volatility clustering over time.

The fractional diffusion equation with Lévy processes is particularly suitable for modeling such dynamics, as it incorporates both stochastic volatility and jump behavior. Specifically, stochastic volatility is modeled using fractional Brownian motion to capture long-range dependence, while Lévy processes are used to represent discontinuities and sudden shocks in asset prices.

Using R statistical software, the model integrates stochastic volatility driven by fractional Brownian motion and jump intensity governed by Lévy processes. In addition, risk-neutral return distributions are considered, which are essential for pricing financial derivatives such as options.

The simulation results confirm the presence of fat tails, skewness, and volatility clustering, thereby demonstrating the capability of the proposed model to capture key features of real financial market behavior.

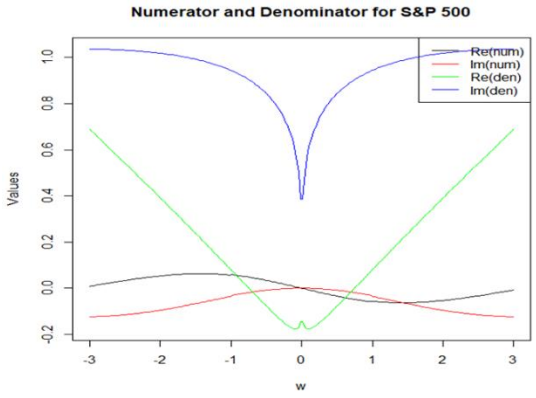


Figure 1: Reference: R statistical software by the researcher.

6.2.2 iShares Europe ETF (IEV) Market Dynamics

The IEV tracks a broad range of European equities and is influenced by various regional factors, including macroeconomic conditions such as economic growth, inflation, and interest rates, as well as political events, including elections, geopolitical tensions, and regulatory changes.

Compared to the S&P 500, the IEV exhibits distinct market characteristics. As illustrated in Figure 2, the level of volatility is generally lower and more regionally constrained than the global volatility observed in U.S. markets. Although fat-tailed behavior is still present, extreme return movements occur less frequently. In addition, price jumps are typically associated with regional shocks, such as major political events (e.g., Brexit), rather than global macroeconomic disruptions.

The fractional diffusion equation with Lévy processes is well suited to modeling these dynamics, as it accounts for both long-range dependence and discontinuities in asset prices. In this framework, stochastic volatility is modeled using fractional Brownian motion, while Lévy processes capture jump behavior, albeit with lower intensity compared to the S&P 500.

To further evaluate the model, numerical simulations were conducted using R statistical software. The simulation incorporates stochastic volatility driven by fractional Brownian motion and jump components governed by Lévy processes, while also considering risk-neutral dynamics relevant for pricing financial derivatives.

The results, presented in Figure 2, indicate moderate fat tails, reflecting less frequent extreme movements in European markets. Volatility clustering is also observed, although it is more stable and less pronounced than in the S&P 500. Furthermore, the lower intensity of jumps suggests relatively smoother market dynamics compared to U.S. equities.

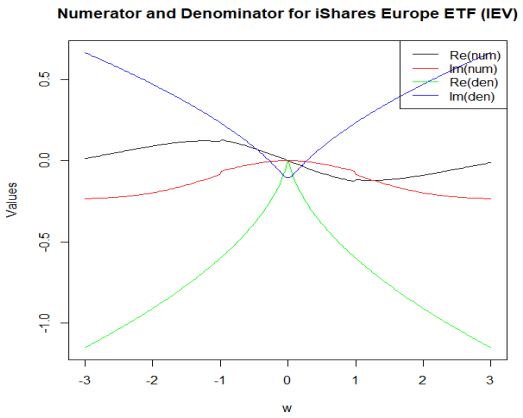


Figure 2: Reference: R statistical software by the researcher.

6.3 Numerical Simulation and Results

The S&P 500 index over the period from January 1, 2014, to December 31, 2019, is considered for analysis.

Figure 3 illustrates the behavior of the numerator and denominator functions within the framework of the fractional diffusion equation with Lévy processes applied to the S&P 500 index. Specifically, it presents the real and imaginary components of both functions over the range of w values from −3 to 3.

The real and imaginary parts of the numerator function are represented by the blue and red lines, respectively, while the green and purple lines correspond to the real and imaginary parts of the denominator function. The results reveal smooth and continuous behavior of both functions across the specified range.

Notably, neither the numerator nor the denominator functions exhibit abrupt changes or discontinuities. This suggests that, within the considered representation, the model produces a continuous approximation of the underlying financial dynamics rather than explicitly capturing jump behavior.

Overall, the plot provides insight into the mathematical properties of the fractional diffusion equation with Lévy processes and its application to financial time series data, highlighting its ability to represent stable and continuous dynamics in the S&P 500 index.

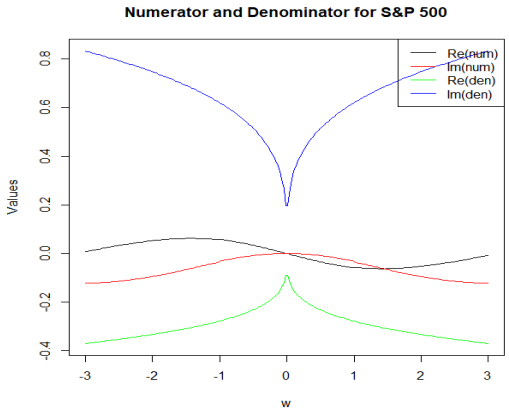


Figure 3: Reference: R statistical software by the researcher.

7 CONCLUSIONS

This paper has presented a novel framework that integrates fractional diffusion dynamics with Lévy-driven jumps, extending the classical Heston model to better capture the complexities of financial markets. By embedding fractional Brownian motion within a stochastic volatility setting, we have addressed significant empirical features such as volatility clustering, heavy tails, and sudden market jumps, which are often inadequately modeled by traditional approaches. The incorporation of fractional Brownian motion introduces long-memory effects, allowing the model to reflect persistent behavior observed in financial time series. This is crucial for accurately modeling asset prices, as it acknowledges the reality of market dynamics where past price movements influence future behavior. Moreover, the use of Lévy processes enables the model to account for discontinuous jumps, thereby providing a more realistic representation of extreme events that frequently occur in financial markets. Through the derivation of a Fourier transform representation for option pricing, we have established a robust mathematical foundation for the proposed model. The Monte Carlo simulation scheme further enhances the practical applicability of our approach, allowing for the numerical evaluation of complex stochastic integrals. Additionally, the implementation of maximum likelihood estimation (MLE) for parameter calibration ensures that our model can be

effectively tailored to fit empirical financial data, enhancing its relevance for practitioners. The application of the model to real financial data, including the S&P 500 index and the iShares Europe ETF, demonstrates its potential to improve the accuracy of option valuation and the measurement of market risk. The results suggest that our framework provides a more comprehensive understanding of market dynamics compared to classical models, particularly in explaining the observed phenomena of volatility clustering and the heavy-tailed nature of financial returns. Despite the advancements presented in this paper, it is essential to acknowledge the limitations and areas for future research. While our model offers a significant step forward, further exploration is needed to refine the integration of fractional dynamics and jump processes. Future work could focus on extending the framework to incorporate additional market factors, such as interest rates and macroeconomic indicators, which could further enhance predictive capabilities. Moreover, the robustness of the model across different asset classes and market conditions should be investigated. Conducting stress tests and scenario analyses will be vital in assessing the model's performance under extreme market conditions, thus ensuring its applicability in risk management and derivative pricing. In conclusion, the fractional diffusion–Lévy process framework proposed in this paper represents a meaningful advancement in financial modeling. By addressing both long memory and discontinuities, the model not only enhances theoretical understanding but also provides practical tools for market practitioners. As financial markets continue to evolve, the need for sophisticated models that can accurately capture their complexities becomes increasingly critical. This research contributes to that objective, paving the way for future innovations in financial modeling and analysis.

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Nu Drop: A Secure Document Request and Online Payment System

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Keywords: Document Request System, Online Payment, Higher Education, Digital Transformation, Secure QR Verification.

Abstract: The manual nature of requesting documents in paper form and over-the-counter payments has continued to exist in many higher education institutions, thus creating long lines, misplaced forms, delays in processing, and exposure to document tampering. To counter these issues, this study designed and developed NU DROP, a secure, web-based system that uniquely integrates document requests with online payment processing in a single platform tailored for Higher Education Institutions (HEI). The system allows for online document requests, status tracking in real time, and multi-channel payments (with online facilities, such as GCash and PayMaya, and over the counter via SM Bills). The development process followed the Scrum methodology and took into consideration interviews, field observation, and document analysis. Key contributions include: 1) an end-to-end process unifying the registrar-accounting-user workflows; 2) QR-based verification to detect tampering of issued PDFs using server-validated cryptographic hashes; 3) inclusive payment options catering to both e-wallet and cash-based users; and 4) role-based dashboards with audit logging for transparency and accountability. Early stakeholder walkthroughs show evidence of better turnaround time visibility, less manual follow-up, and more consistent recordkeeping.

1 INTRODUCTION

Document processing in many higher education institutions remains a manual task, which sometimes manifests as long queues, misplaced forms, limited office hours, and insecure verifications of official records [1], [2]. Such problems tend to burden administrative staff and decrease user satisfaction with the services provided by students, alumni, and faculty [3]. In certain institutions, requestors will fill in paper forms, pay at cashier windows, and return receipts to other offices for validation – this tiresome process not only makes it error-prone but also difficult to track status, thereby further delaying service delivery [4].

Hence, this study introduces NU DROP, which totally digitizes the entire document request and payment workflow via a secure web-based platform [2]. This fully certified online submission facilitates online payment on any of the given inclusive payment channels and gives a tracking tool to monitor request status in real time. The administrator manages and monitors requests via a central dashboard for user's requests, payment validation, and document issuance. And to preserve the authenticity of documents issued by NU DROP, an instant on-the-spot validation of issued documents is accomplished through a QR-based tamper-resistant verification mechanism.

The NU DROP system stands apart from existing systems in other universities in three major aspects: first, the integration of registrar and accounting workflows to minimize delays due to reconciliation; second, the provision for payment through an e-wallet as well as over the counter; and third, an approach to document verification that resists tampering, which essentially employs QR-linked cryptographic hashes.

The remainder of this paper is organized as follows. Section 2 presents the related works and gaps in existing systems for document requests and payments. Section 4 outlines the methodology, including the research design, data collection, and system development process. Section 5 describes the features and technical implementation of the NU DROP system. Section 5 discusses the results and contributions, while Section 6 provides the conclusion and recommendations for future work.

2 RELATED WORK AND GAP

Many universities have adopted online requests and payment portals, though these typically provide only basic features such as request submission, limited tracking, and partial payment integration [2]. Significant gaps remain [5], including administrative fragmentation where registrar and accounting departments operate separate systems requiring manual reconciliation, a lack of payment inclusion for cash-preferred users without access to cards or banks, and weak authenticity assurance since issued documents are still prone to tampering when only basic watermarks are used.

NU DROP gets rid of these gaps by unifying interdepartmental workflows, providing inclusive multi-channel payments, and a QR verification component embedded with tamper-resistant features. Research on electronic payment systems in Philippine HEIs [6] confirms the importance of offering diverse payment options to accommodate different user preferences.

3 OBJECTIVES

The primary objective of this study is to develop and organize a secure-based installation system that is user-centric, facilitates the request and payment of documents while preserving the authenticity of the issued records.

Specifically, this study sought to address the following objectives:

- To enable web-based request submission with status tracking and notifications.
- To facilitate inclusive secure payment options, i.e., GCash, PayMaya, and SM Bills.
- To apply QR-based tamper detection for issued documents.
- To develop a dashboard for registrar, accounting, and admin roles will also have audit logging features.

The contributions of this study are fourfold. First, the entire process has been automated, significantly reducing reliance on manual procedures. Second, the system provides greater integration of payments by accommodating both electronic and cash-preferred customers. Third, a tamper-proof QR verification mechanism is implemented to ensure the authenticity of issued documents. Finally, the study presents a realistic yet general architectural model that can be adopted and adapted within higher education contexts.

4 METHODS

This section outlines the methodological approach undertaken in the design and development of the NU DROP system. It describes the process of developing the system using SCRUM.

4.1 Scrum Model

Using Scrum Methodology [7] encourages continuous iterative development and the constant engagement of all relevant stakeholders. Sprint planning, backlog preparation, execution, and reviews served the team in iterative refinement of the NU DROP system based on user feedback.

4.2 Data Collection

Interviews were conducted with students, staff, and administrators to identify pain points in the existing processes [8]. In addition, field observations were carried out in the registrar and accounting offices to directly observe workflow bottlenecks as they occurred. Document analysis was also performed on historical request logs and payment records to determine peak transaction periods and recurring issues.

5 RESULTS AND DISCUSSION

5.1 The Main Feature

The NU DROP system offers a range of features designed to streamline document requests and payments. For users, the system provides online request submission, real-time status tracking, and access to transaction history. The registrar dashboard supports the processing of requests, monitoring of document status, and workload management. The accountancy dashboard enables payment confirmation, reconciliation, and financial report generation, while administrative tools allow for the management of user accounts, roles, document types, and payment methods. Finally, a QR-based online verification mechanism is integrated to confirm the authenticity of issued PDF documents and prevent tampering.

5.2 Technical Implementation

The technical implementation of the NU DROP system was carried out using a modern web technology stack [9]. The backend was developed with Laravel 10 running on PHP 8.x, while the frontend employed Blade Templates integrated with the Tailwind CSS framework to ensure a responsive and consistent user interface. MySQL database was used for data storage and management. System notifications were implemented through email, with optional support for Firebase Cloud Messaging (FCM) to enable real-time alerts. Security measures included Laravel Sanctum for authentication, CSRF protection, role-based access control, and audit logging to ensure data integrity and accountability. To further enhance trust, a tampering detection mechanism was integrated, where each issued PDF is assigned a SHA-256 hash stored on the server, and a QR code is generated pointing to a verification endpoint for authenticity checks.

5.3 NU DROP Web Application Screenshots

Figure 1 is the Home Page of the NU DROP system serves as the primary entry point for users, providing a clean and intuitive interface that highlights the system's core functions. From this page, students and staff can quickly access the online document request feature, view the real-time status of their pending requests, and review their transaction history. Clear navigation menus and responsive design elements ensure accessibility across devices, while quick links to support, payment channels, and login options streamline the user experience. The home page is designed to be user-centric, minimizing complexity while giving immediate visibility to the most frequently used services.

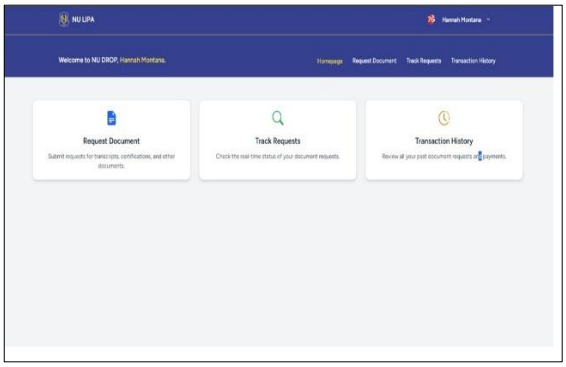


Figure 1: Home page.

Figure 2 is the NU DROP Admin Dashboard. It is a centralized system providing administrators with a general view of what happens in the system, especially in managing the online document requests and payment transactions. It provides the admin with key information regarding the total number of documents available, total requests made by users, status of requests – not verified, verified, pending, on process, ready for pickup, or released. This will essentially help the admin monitor the flow of requests effectively. Also, included in the dashboard is a revenue summary that shows weekly, monthly, and annual income generated from online payments. At the lower section, there is a visual chart that presents the top requested documents out there, like the Transcript of Records and Certificate of Registration, so that administrators can get an idea of user demand and make informed decisions. In summary, the admin dashboard has been conceived to facilitate backend processes, thus enhancing accountability and promoting quick service delivery.

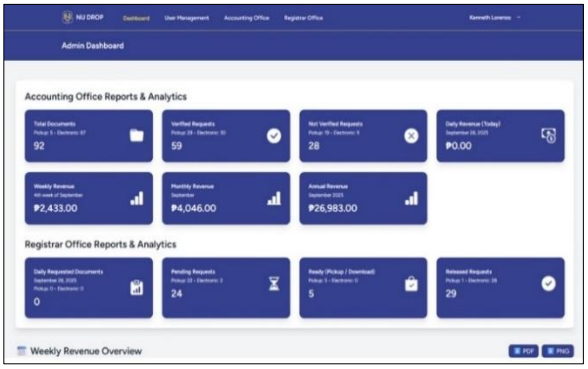


Figure 2: Admin dashboard.

Figure 3 is the NU DROP Accounting Office Dashboard. The Accounting Dashboard stands as a neat arrangement for initiating and monitoring document payment transactions. It provides important information on the overall requests versus unverified requests versus verified requests, thus enabling accounting staff to validate and track payment status easily. Financial summaries are also presented, covering income trends such as weekly, monthly, and yearly sales figures, thus providing an accounting office with a full understanding of income trends. Another feature of the dashboard is the Weekly Revenue Overview, providing a graphical way of assessing financial activity over time. This interface ensures utmost efficiency within the accounting office while promoting the accuracy and transparency of payment procedures.

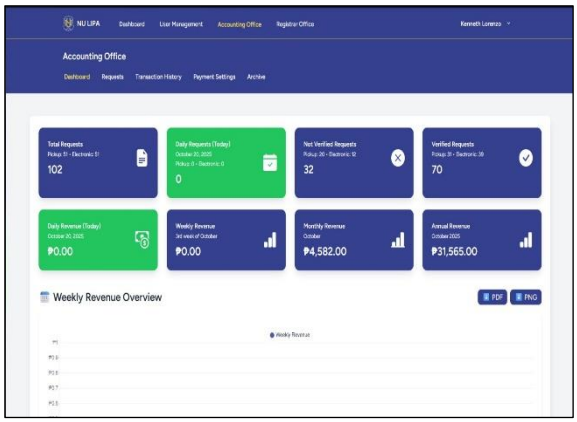


Figure 3: Accounting office dashboard.

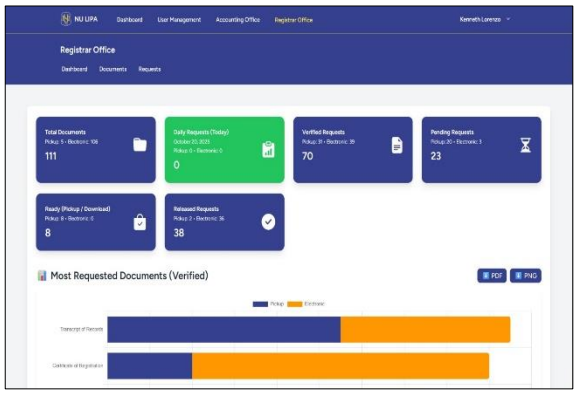


Figure 4: Registrar dashboard.

Figure 4 is the NU DROP Registrar Office, serves the purpose of sending requests for documents related to the activities of the registrar. It holds significant details such as the number of document types, verified requests, pending requests, documents presently being processed, and documents that have already been collected or sent for release. This feature provides complete supervision for administrative staff to effectively monitor and take necessary actions on the status of requests. The dashboard also features a graphical representation in a chart of Most Requested Documents, which indicates the most requested documents by users, such as the Transcript of Records or Certificate of Registration. This improves the ease of and more efficient handling of documents, prioritizing, assigning resources, etc.

As shown in Figure 5, the settings page for payments provides options for changing the possible methods of payment, for example, e-wallets with an uploaded QR code by an administrator.

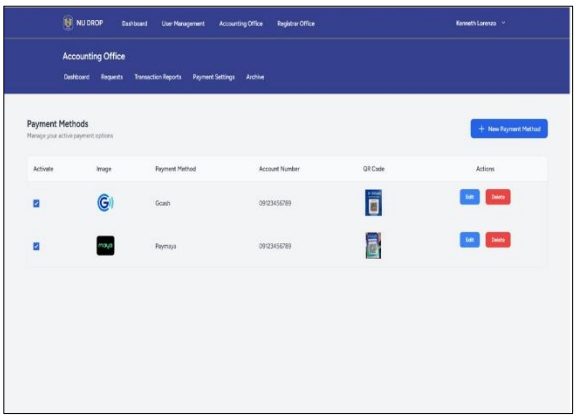


Figure 5: Payment settings.

Figure 6 presents the Request Documents Page, where students can request official records such as transcripts and certificates directly from the university. The interface allows users to browse the list of available documents, select the required type, and complete the request online. This module eliminates the need for in-person visits to the registrar's office, offering a more convenient and efficient process for both current students and graduates.

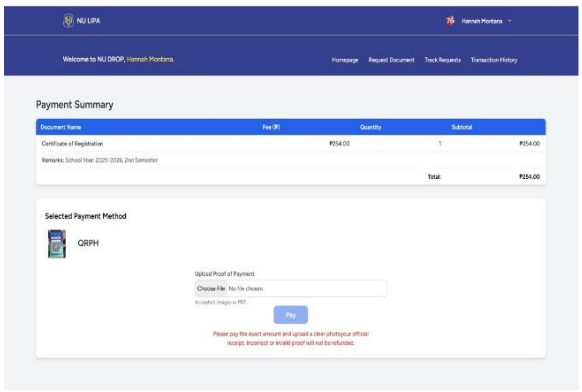


Figure 6: Request document page.

NU DROP addresses the limitations of manual processes by providing faster, more efficient, transparent, and secure services [10]. Initial feedback indicates that the system's unified workflows significantly reduce reconciliation delays between departments [11]. Its inclusive payment options improve accessibility for a broader range of users, while the integration of QR-based verification ensures more reliable document authenticity. Collectively, these features represent exclusive capabilities and unique differentiators of NU DROP,

highlighting its originality and technological value compared to existing systems.

6 CONCLUSIONS

NU DROP shows how a digital transformation can facilitate the streamlining of administrative workflows in higher education institutions. With the inclusion of payment options, anti-tamper verification, and centralized dashboards, the system innovates into authentication, inclusivity, and accountability, far beyond the traditional online portal. Future developments will look toward integrating direct payment gateways and support for mobile applications.

Although the NU DROP system demonstrated improvements in streamlining document requests and payments, certain limitations remain. The system relies on stable internet connectivity, which may affect access for users in areas with limited or unstable networks. In addition, while security mechanisms such as QR-based verification and role-based access were implemented, further testing under large-scale deployment scenarios is needed to validate performance and scalability. For future development, the system may be enhanced by integrating advanced analytics for usage monitoring, expanding payment channels, and incorporating mobile application support to further improve accessibility and user experience.

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Maximum Likelihood Estimation for the Weibull-Burr Distribution

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Keywords: Weibull- Burr Distribution, Weibull Distribution, MLE, MSE, Simulation.

Abstract: This study introduces a new family of distributions known as the five-parameters Weibull- Burr distribution. This study aims to present a new family of Weibull-Burr distributions by utilizing the maximum likelihood estimation (MLE) method to determine the efficiency of the exponential family through the mean square error (MSE) by utilizing Monte Carlo simulation experiments by using the R program. It is designed to offer greater flexibility in the modeling of the financial, and actuarial data. The distribution in view presents five parameters, being thus capable of describing very peculiar hazard rate behaviors, and extreme values. Among the key statistical properties derived in this paper are the probability density function, cumulative distribution function, and moments of the distribution. Further, the paper concentrates on parameter estimation of the distribution by the method of MLE. The log-likelihood function was formulated, and processed, followed by parameter estimation, and further by the simulation under different sample sizes. Simulation results show that the proposed model can effectively address complex data structures. These results clearly indicate that the Weibull –Burr Model offers a promising alternative to the classical distributions used in modeling in finance, and actuarial domains.

1 INTRODUCTION

In recent years, the growing interest in research has been induced for developing classical probability models to incorporate into its fold, and provide more flexible, and accurate representation of complex real world data [1]. The developments involved expanding the number of parameters or applying some transformation on the original distributions or constructing hybrid models by combining two or more distributions [2]. The foremost feature of the statistical modification is to enhance the precision of inference, and aside from that, changes adapted for asymmetric behavior or extreme values for data, examples of which are financial or actuarial data. This study intends to present a new family of Weibull - Burr distributions through the MLE method for efficient estimation of the parameter based on the Monte Carlo simulation experiments for mean square error (MSE). In this study, R is introduced for the experimental section. In this line of research, the Burr distribution can be considered one of the paramount distributions in representing actual data with extreme behaviors and varied risk functions, forming an extremely flexible new distribution when combined with other distributions such as the Weibull distribution, namely, the five-parameter Weibull-Burr distribution [3]. The proposed distribution combines the properties of two distributions and hence can stand as a better candidate for modeling high-variance data. Some important contributions made in previous research are discussed with the synthesis of those findings, building upon which new developments in this field will be initiated. Some of the relevant previous researches are listed here. A new procedure for the generation of a family of Weibull probability distributions was introduced in (2015) using the logistic Weibull distribution [4]. In (2017), researchers presented a newer generalized distribution that better fits the Weibull and some generalizations, i.e., the alpha-powered Weibull distribution [5]. The next year saw the proposal of a new family of univariate x-Weibull distributions with two sub models that belong to the said family [6]. In (2020), researchers proposed a study titled "A Family of Single-Inverse Weibull Distributions," which provides high flexibility in analyzing life-span data [7]. In (2021), researchers proposed a new class of extreme value statistical distributions specifically designed for modeling complex financial, and actuarial data [8]. In (2023), researchers proposed a Weibull distribution with an estimable shift

parameter [9]. In (2025), researchers proposed a study of a new family of Lomax-x-shift distributions: Properties and estimation on financial, and actuarial data [10].

2 WEIBULL –BURR DISTRIBUTION

The new five-parameter Weibull- Burr distribution is an advanced extension of continuous probability distributions, it is designed for modeling the complex three-parameters financial, actuarial, and engineering data with the time interval (0,∞). This distribution combines the properties of the Burr distribution, known for its flexibility in handling data with the extreme values, and the Weibull distribution, which is popular in modeling data related to reliability, and failure times, providing a powerful framework for analyzing the complex multi-parameter data. The new distribution also aims to improve the data fit by introducing additional parameters that allow controlling over shape, scale, and displacement, making the model capable of representing a wider range of data behaviors compared to traditional distributions. The proposed distribution can represent different types of data, such as the extreme values data or data with a positive or negative skewness. Applying the new distribution on the financial, and actuarial data for the output distribution makes the new distribution more accurate in the modeling of the large losses, which is critical in the financial risk analysis [11], [12]. It also allows processing the complex data while maintaining a clear statistical interpretation of the distribution parameters [13], [14]. The general formula for the distribution as below:

Regarding a random variable T, let h(t) be its pdf, where $T \in [a, b]$ for $-\infty \le a < b < \infty$. Similarly, let W[G(x; ζ)] be its CDF, contingent upon the vector parameter ζ meeting the following requirements:

- W[G(x; ζ)] ∈ [a, b];
- In addition to being monotonically rising, W[G(x; ζ)] is differentiable;
- W[G(x; ζ)] → a as x → −∞ and W[G(x; ζ)] → b as x → +∞.

The CDF associated with the T-X family of distributions was recently defined by [5]:

$$F(x) = \int_a^{w[G(x);\xi]} h(t)dt \quad (1)$$

In this article, we propose the following staggered transformation:

$$W[G(x; \zeta)] = x\,(G(x) + m),$$

where $x \ge 0$, $G(x; \zeta)$ is the CDF of one of the classical models, and $m \ge 0$ is a constant representing the shift parameter. W[G(x; ζ)] on [0, +∞] satisfies the aforementioned requirements. We study here with h(t) the density function of the Weibull function whose support is for $x \ge 0$. This gives us a new family of shifted Weibull distributions whose CDF is defined b:

$$F(x)=\int_a^{x[G(x)+m]} h(t)dt, \quad (2)$$

$$F(x)=1- e^{-\left[\frac{xG(x)+mx}{\lambda}\right]^{\theta}}. \quad (3)$$

where $x \ge 0$, $\theta = (\zeta, \alpha, \lambda, m) \ge 0$.

This distribution function is differentiated based on x. As a result, we get:

$$F(x) = 1 - e^{-\left[\frac{x-x(1+x^{\alpha})^{-\beta}+mx}{\lambda}\right]^{\theta}}, \quad (4)$$

$$f(x)=\frac{\theta}{\lambda^{\theta}}\,[xG(x) + mx]^{\theta-1}\,[xg(x) + G(x) + m]\; e^{-\left[\frac{xG(x)+mx}{\lambda}\right]^{\theta}}, \quad (5)$$

$$f(x)= \frac{\theta}{\lambda^{\theta}}[x - x(1 + x^{\alpha})^{-\beta}+mx]^{\theta-1}[1+\alpha\beta x^{\alpha}(1 + + x^{\alpha})^{-\beta-1} + \left(1 + x^{\alpha}\right)^{-\beta} + m\right] \quad e^{-\left[\frac{x-x(1-x^{\alpha})^{-\beta}+mx}{\lambda}\right]^{\theta}}, \quad (6)$$

$$S(t)= e^{-\left[\frac{x-x(1+x^{\alpha}]^{-\beta}+mx}{\lambda}\right]^{\theta}}, \quad (7)$$

$$h(x) = \frac{\theta}{\lambda^{\theta}}[x-x(1+x^{\alpha})^{-\beta}+mx]^{\theta-1}[1+\alpha\beta x^{\alpha}(1+x^{\alpha})^{-\beta-1}+ \left(1+x^{\alpha}\right)^{-\beta} + m\,], \quad (8)$$

The purpose of the distribution function: Weibull-Burr distribution as a statistical model can be used in the modeling of the financial and actuarial data. The probability density function (PDF) “has a condition” that must be satisfied, as below [15]:

1) Non negative;
2) The condition for the cumulative distribution function (CDF) is that it does not exceed one [16], [17], (Table 1).

$$\lim_{x-0} F(x) = 0, \quad (9)$$

$$\lim_{x-\infty} F(x) = 1. \quad (10)$$

Table 1: The properties of the Weibull- Burr distribution.

Properties/Formula
Mean
$\mathbf{E}(x)= Ab\frac{\Gamma_{(1)}}{\theta+\alpha j}+\ Ab^{-\frac{1}{\theta+\alpha j}+1}$
Variance
$V(x)= Ab\frac{\Gamma_{(2)}}{\theta+\alpha j}+\ Ab^{\left(-\frac{2}{\theta+\alpha j}+1\right)}-(Ab(\frac{\Gamma_{(1)}}{\theta+\alpha j}+\ Ab^{(-\frac{1}{\theta+\alpha j}+1)})^2$
Moment
$Ab\frac{\Gamma_{(r)}}{\theta+\alpha j}+1\ Ab^{(-\frac{r}{\theta+\alpha j}+1)}$
Skewness
$\frac{Ab(\frac{\Gamma_{(3)}}{\theta+\alpha j}+\ Ab^{(-\frac{3}{\theta+\alpha j}+1)}-3\ Ab(\frac{\Gamma_{(1)}}{\theta+\alpha j}+\ Ab^{(-\frac{1}{\theta+\alpha j}+1)}Ab(\frac{\Gamma_{(3)}}{\theta+\alpha j}+\ Ab^{(-\frac{3}{\theta+\alpha j}+1)}+2(\ Ab(\frac{\Gamma_{(1)}}{\theta+\alpha j}+\ Ab^{(-\frac{1}{\theta+\alpha j}+1)})^3}{[\ Ab(\frac{\Gamma_{(2)}}{\theta+\alpha j}+\ Ab^{\left(-\frac{2}{\theta+\alpha j}+1\right)}-(Ab(\frac{\Gamma_{(1)}}{\theta+\alpha j}+\ Ab^{(-\frac{1}{\theta+\alpha j}+1)})^2]^{\frac{3}{2}}}$
Kurtosis
$\frac{Ab(\frac{\Gamma_{(4)}}{\theta+\alpha j}+\ Ab^{(-\frac{4}{\theta+\alpha j}+1)}-4Ab(\frac{\Gamma_{(1)}}{\theta+\alpha j}+\ Ab^{(-\frac{1}{\theta+\alpha j}+1)}Ab(\frac{\Gamma_{(3)}}{\theta+\alpha j}+\ Ab^{(-\frac{3}{\theta+\alpha j}+1)}+6(Ab(\frac{\Gamma_{(1)}}{\theta+\alpha j}+\ Ab^{(-\frac{1}{\theta+\alpha j}+1)})^2-\ Ab(\frac{\Gamma_{(2)}}{\theta+\alpha j}+1\ Ab^{(-\frac{2}{\theta+\alpha j}+1)}-3(Ab(\frac{\Gamma_{(1)}}{\theta+\alpha j}+1\ Ab^{(-\frac{1}{\theta+\alpha j}+1)}}{(Ab(\frac{\Gamma_{(2)}}{\theta+\alpha j}+\ Ab^{(-\frac{2}{\theta+\alpha j}+1)}-(Ab(\frac{\Gamma_{(1)}}{\theta+\alpha j}+\ Ab^{(-\frac{1}{\theta+\alpha j}+1)})^2)^2}$
Moment generating function
$\sum_{k=0}^{\infty}\frac{(t)^k}{k!}\ \Gamma(\frac{k}{\theta+j\alpha})+Ab^{-\frac{k}{\theta+j\alpha}}$

$$\frac{\partial lnL}{\partial\theta}=\frac{n}{\theta}-n\ \ln(\lambda)+\sum_{i=1}^{n}\ln[xi-xi(1+xi^{\alpha})^{-\beta}+mxi]-\sum_{i=1}^{n}[xi-xi(1+xi^{\alpha})^{-\beta}+mxi]^{\theta}.\ln[xi-xi(1+xi^{\alpha})^{-\beta}+mxi]+Ln\lambda.\lambda^{-\theta}\sum_{i=1}^{n}[x_i-x_i(1+x_i^{\alpha})^{-\beta}+mx_i]^{\theta} \quad (13)$$

$$\frac{\partial lnL}{\partial\alpha}=\ \sum_{i=1}^{n}\left[xi(1+xi^{\alpha})^{-\beta}\ln(1+xi^{\alpha})\right)\sum_{i=1}^{n}\frac{-(\beta^2\mp\beta)\alpha^2xi^{\alpha+1}(1+xi^{\alpha})^{-\beta-2}+(1+xi^{\alpha})^{-\beta}(\beta\alpha^2xi^{\alpha-1}+xi\beta)-\beta xi^{\alpha}\ln(xi)(1+xi^{\alpha})^{-\beta-1}}{[1+\alpha\beta xi^{\alpha}(1+xi^{\alpha})^{-\beta-1}-(1+xi^{\alpha})^{-\beta}+m]} \quad (14)$$

$$\frac{\partial lnL}{\partial\beta}=\sum_{i=1}^{n}\frac{xi(1+xi^{\alpha})^{-\beta}\ln(1+xi^{\alpha})}{[xi-xi(1+xi^{\alpha})^{-\beta}+mxi]}+\sum_{i=1}^{n}\frac{\beta\alpha xi^{\alpha}(1+xi^{\alpha})^{-\beta-1}\ln(1+xi^{\alpha})-(1+xi^{\alpha})^{-\beta-1}\alpha xi^{\alpha}+(1+xi^{\alpha})^{-\beta}\ln(1+xi^{\alpha})}{[1+\beta\alpha xi^{\alpha}(1+xi^{\alpha})^{-\beta-1}-(1+xi^{\alpha})^{-\beta}+m]}, \quad (16)$$

$$\frac{\partial\ Ln\ L}{\partial m}=(\theta-1)\sum_{i=1}^{n}\frac{xi}{[xi-xi(1+x_i^{\alpha})^{-\beta}+mxi]}+\sum_{i=1}^{n}\frac{1}{[1-\beta\alpha x_i^{\alpha}(1+x_i^{\alpha})^{-\beta-1}-(1+x_i^{\alpha})^{-\beta}+m}-\theta\lambda^{-\theta}\sum_{i=1}^{n}[xi-xi(1+x_i^{\alpha})^{-\beta}+mxi]^{\theta-1}(xi) \quad (18)$$

2.1 Maximum Likelihood Method (MLE)

It is considered one of the most widely used methods in statistics for estimating parameters [18], [19]. It was contributed by Joseph Lagrange, and Daniel Bernoulli, and was proposed by the British scientist Ronald Fisher in the early twentieth century. He was first presented it in a research paper, due to its useful properties, including Sufficiency, impartiality, and reliability. This method aims to find estimated values for the parameters to be estimated, thus maximizing the probability function. If the random variable (x) has the probability density function (PDF) of the proposed distribution, then the maximum probability function for the independent random variables (xi) with the same distribution is as follows, [20].

$$\begin{aligned}\ln L=\ & n\ln(\theta)-n\,\theta\ln(\lambda)+(\theta-1)\sum_{i=1}^{n}\ln[xi-xi(1+x_i^{\alpha})^{-\beta}+mx_i]+\sum_{i=1}^{n}\ln[1+\alpha\beta x_i^{\alpha}\left(1+x_i^{\alpha}\right)^{-\beta-1}+\\ &\left(1+x_i^{\alpha}\right)^{-\beta}+m]]-\lambda^{-\theta}\sum_{i=1}^{n}[\,xi-xi(1+xi^{\alpha})^{-\beta}+mxi\,]^{\theta}\end{aligned} \quad (11)$$

To obtain the MLE of the parameters of the Weibull-Burr distribution [21], [22], it can be deriving the (7) as follows (12) – (18):

$$\frac{\partial lnL}{\partial\lambda}=-\frac{n\theta}{\lambda}+\theta\lambda^{-\theta-1}\sum_{i=1}^{n}[xi-xi(1+xi^{\alpha})^{-\beta}+mxi]^{\theta}, \quad (12)$$

$$-\sum_{i=1}^{n}\theta\lambda^{-\theta}\left[xi-xi\left(1+xi^{\alpha}\right)^{-\beta-1}+mxi\right]^{\theta-1}\beta xi^{\alpha+1}\ln(xi)(1+xi^{\alpha})^{-\beta-1}\ldots \quad (15)$$

$$-\lambda^{\theta}\theta\sum_{i=1}^{n}[xi-xi(1-xi^{\alpha})^{-\beta}+mxi]^{\theta-1}(xi(1-xi^{\alpha})^{-\beta}\ln(1-xi^{\alpha})) \quad (17)$$

2.2 The Experimental Simulation

The behavior of the probability density function (PDF) and cumulative distribution function (CDF) of the Weibull–Burr distribution for different parameter values is illustrated in Figure 1. Different default values were used for each of the five distribution parameters to complete five simulation experiments, with repetition once, and default values for each parameter in the five models and sample sizes (n=25, 50, 75, 125, 200) as shown in the Table 2 and default values. The number of times the simulation experiments were 1000 times. Accordingly, the estimated Weibull- Burr distribution parameters obtained from the simulation study using the MLE are presented in Tables 3, 5, 7, 9, and 11, while the corresponding MSE values are presented in Tables 4, 6, 8, 10 and 12.

The purpose is to demonstrate the efficiency of the MLE. The comparison criterion, the mean square error (MSE), is used according to the following (19):

$$\text{MSE} = \frac{\sum_{i=1}^{r}(\widehat{\theta i}-\theta)^2}{r}. \qquad (19)$$

Table 2: The values of the default parameters (α, β, λ, θ, m).

α	9.8	4.5	3.5	1.5	0.5
β	0.1	0.35	0.5	0.5	0.5
λ	0.04	0.1	1.4	1.6	1.5
θ	1	1	2	0.5	0.5
m	0.06	0.15	0.08	1.25	0.1

Table 3: The estimated values of the parameters (α, β, λ, θ, m,). for the first experiment.

n	Parameter	Estimator
25	α	10.17533
50	β	0.112606
75	λ	0.044613
125	θ	1.004373
200	m	0.066892

Table 4: The (MSE) method for the first experiment.

n	Parameter	MSE
25	α	1.700772
50	β	0.003185
75	λ	0.00378
125	θ	0.29549
200	m	0.009087

Table 5: The estimated values of the parameters (α, β, λ, θ, m,). for the second experiment.

n	Parameter	Estimator
25	α	4.916392
50	β	0.445059
75	λ	0.127591
125	θ	1.029991
200	m	0.194455

Table 6: The (MSE) method for the second experiment.

n	Parameter	MSE
25	α	1.396555
50	β	0.21675
75	λ	0.145187
125	θ	1.462275
200	m	0.408576

Table 7: The estimated values of the parameters (α, β, λ, θ, m,). for the third experiment.

n	Parameter	Estimator
25	α	3.535887
50	β	0.500019
75	λ	1.425153
125	θ	2.027436
200	m	0.091558

Table 8: The MSE method for the third experiment.

n	Parameter	MSE
25	α	0.027641
50	β	0.002642
75	λ	0.34137
125	θ	0.433154
200	m	0.060002

Table 9: Shows the estimated values of the parameters (α, β, λ, θ, m,). for the fourth experiment.

n	Parameter	Estimator
25	α	1.522018
50	β	0.512781
75	λ	1.700785
125	θ	0.504265
200	m	1.34772

Table 10: The MSE method for the fourth experiment.

n	Parameter	MSE
25	α	0.013857
50	β	0.18419
75	λ	0.238929
125	θ	0.006866
200	m	0.193461

Table 11. The estimated values of the parameters (α, β, λ, θ, m,). for the fifth experiment.

n	Parameter	Estimator
25	α	0.510069
50	β	0.540635
75	λ	1.701895
125	θ	0.511138
200	m	0.130527

Table 12: The MSE method for the fifth experiment.

n	Parameter	MSE
25	α	0.013565
50	β	1.545329
75	λ	1.589458
125	θ	0.104269
200	m	0.033266

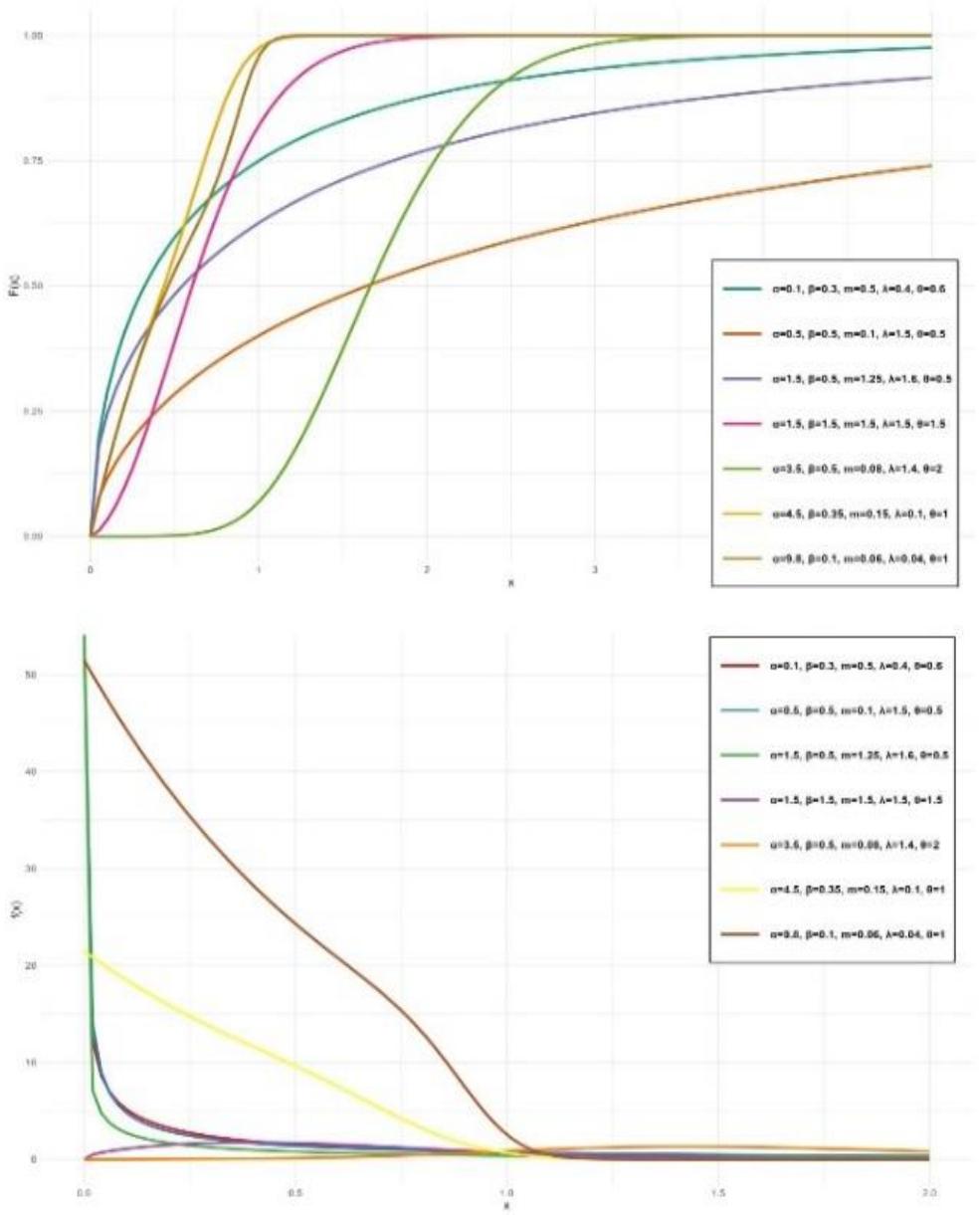


Figure 1: The behavior of (CDF and PDF) functions for Weibull-Burr Distribution with various parameters.

3 CONCLUSIONS

In this research, it provided a new statistical distribution is called Weibull - Burr distribution. The efficiency of the MLE was proven on the five-parameter Weibull- Burr distribution. The results were showed that the parameters estimate approach the true values were increasing sample size (n), and the MSE values were decrease with increasing sample size n. For some parameters, such as (λ, m and θ), the estimates were increased at small sample sizes, and the MSE was initially high, then stabilizes with increasing sample size (n). However, (α, β) was more stabled at medium sample sizes. The results were confirmed that increasing in the sample size leaded to a reduction in the error in the estimates for all of the parameters. From sample size (n≥125) and above, the MSE becomes lower than it is.

Also, the simulation results were showed that the accuracy of the parameters estimation for the Weibull - Burr distribution improved significantly with the increasing sample size. Therefore, it is recommended to use a sample size of no less than n=125 to ensure accurate estimates. Estimated the parameters by using the MLE by minimizing the MSE. Also, should be attention to paid to the displacement parameter (m) and the scale parameter (λ), as they may require additional estimations to improve their accuracy in the small samples. In addition, should be monitored the MSE to assess the quality of the estimations in the experiments, which in turn helps reveal the direct effect of sample size on the accuracy of the parameters. Finally, as a future work, it is possible - for example- to use the proposed statistical distribution on the huge dataset of the real-world or mixing the proposed statistical distribution with another statistical distribution and applying it on the real-world dataset.

4 RECOMMENDATIONS

We recommend using the Transformation (T-X) method with other distributions to obtain a new family based on the Weibull-Burr distribution, due to its high flexibility in modeling heavy tailed financial and actuarial data or generating a new family from other distributions. We also recommend using other methods, such as Bayesian methods, to estimate distribution parameters when working with relatively large datasets, as they are more stable and accurate. We also recommend using real data representing larger and more diverse samples from different insurance companies or across multiple time periods to obtain better results.

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Modeling the Impact of Technological Drivers on Investment Attractiveness of Renewable Energy Markets

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Keywords: Renewable Energy, Renewable Energy Country Attractiveness Index, Technology-Specific Indices, Regression Analysis, Investment Attractiveness.

Abstract: The study is dedicated to analyzing the relationship between the Renewable Energy Country Attractiveness Index (RECAI) and technology-specific indices of renewable energy technologies to identify key technological drivers of investment attractiveness in renewable energy markets. The methodology is based on applying General Regression Models for 40 countries, where RECAI serves as the dependent variable, and eight technology-specific indices (onshore wind, offshore wind, solar photovoltaics, concentrated solar power, biomass, geothermal, hydro, battery energy storage systems) serve as independent predictors. The results of the regression analysis demonstrate a statistically significant impact of four technologies on RECAI formation. Solar photovoltaics show the most powerful effect, followed by onshore wind, battery energy storage systems, and offshore wind in terms of impact magnitude. The technologies of concentrated solar power, geothermal, hydro, and biomass proved to be statistically insignificant predictors. Three-dimensional visualization confirmed the synergistic nature of the impact of key technologies and the importance of a diversified technological portfolio for maximizing market attractiveness. The practical value of the study lies in creating an empirically grounded tool that provides a foundation for strategic planning by investors and policymakers of investments in renewable energy at the national level.

1 INTRODUCTION

The global energy transition to renewable energy sources (RES) is gaining increasing importance in the context of combating climate change and ensuring energy security [1]-[4]. According to Bloomberg, global investments in renewable energy reached a record USD 2.1 trillion in 2024 [5], indicating sustained growth in interest in this sector from investors and governments. However, the distribution of investment flows between countries remains uneven [6], necessitating a thorough analysis of factors that determine the investment attractiveness of national RES markets.

The Renewable Energy Country Attractiveness Index (RECAI), developed by consulting company EY, is one of the most influential comprehensive indicators for assessing the investment attractiveness of national renewable energy markets [7]. This index considers a wide range of macroeconomic, infrastructural, and political factors, but its composite nature complicates the understanding of the specific contribution of individual technological components to forming a country's overall rating. At the same time, technological differentiation of RES markets is critically important for investors, as different renewable technologies are characterized by distinct risk profiles, levels of technological maturity, and commercialization potential.

Contemporary research on RES investment attractiveness predominantly focuses on analyzing general macroeconomic determinants or considers individual technologies in isolation, without accounting for their synergistic impact on comprehensive market attractiveness assessment [8]-[11]. For instance, D. Doğan et al. analyzed the relationships between renewable energy consumption, carbon dioxide emissions, economic

growth, financial development, and energy dependence. The authors used the panel regression method to conduct research for 38 countries over the period 1991–2021 based on RECAI. It was established that financial development affects both carbon dioxide emissions and economic growth [12]. Researchers N. Y. Mohamed Yusoff et al. used autoregressive distributed lag based on annual time series data to analyze macroeconomic indicators, including gross domestic investment, domestic investment, foreign direct investment, trade openness, urbanization, financial development, and carbon emission levels on renewable energy in Malaysia. They determined that greater economic development and urbanization increase the share of renewable energy. Conversely, increases in foreign investment, trade liberalization, and carbon emissions may reduce the use of these clean energy sources [13]. G. Osuma and L. Bonga-Bonga studied the impact of foreign direct investment and technological innovations on renewable energy consumption formation. The authors analyzed their joint effect in 20 EU countries during 2013–2023 using the Method of Moments Quantile Regression. Results showed that technological innovations consistently contribute to growth in renewable energy consumption. In contrast, foreign direct investment has a negative impact on renewable energy consumption. Additionally, inflation positively affects renewable energy consumption, indicating that rising energy prices stimulate the transition to alternative sources [14]. O. Prokopenko et al. used a vector autoregressive model to analyze the impact of long-term investments and research and development expenditures in renewable energy on the financial performance of 10 leading industry companies. The obtained results indicate a positive impact of investments and research and development expenditures on key profitability indicators: taxes, depreciation, earnings before interest and taxes, net profit, and return on investment, emphasizing the economic feasibility of financing innovations in renewable energy [15].

However, such a fragmented approach limits the possibilities for comprehensive understanding of synergistic effects. This creates a methodological gap in understanding how specific technological factors interact with each other and shape the overall investment attractiveness of national RES markets.

The aim of the study is to develop an empirical model of the relationship between the Renewable Energy Country Attractiveness Index and technology-specific indices of renewable energy technologies to identify key technological drivers of RES market investment attractiveness. To achieve the stated goal, the following tasks are planned: conduct correlation analysis of relationships between RECAI and eight technology-specific indices; build a multifactor regression model for quantitative assessment of each technology's impact on overall attractiveness index formation; identify statistically significant technological drivers and perform analysis of synergistic effects of key technologies to understand their combined impact on market attractiveness.

2 METHODOLOGY

To assess factors that determine the investment attractiveness of renewable energy markets in the context of transition to energy independence and achieving grid parity, RECAI is used. The methodology for calculating this index is based on five key dimensions (energy imperative, policy stability, project delivery, capital availability, natural resource diversity), which are aggregated through a system of weighting coefficients into a composite index with scores from 1 to 5. Along with calculating the overall RECAI value, additional calculations are performed for the following technology-specific indices [7]:

- onshore wind – electricity generation using wind turbines located on land;
- solar photovoltaics (PV) – technology that converts sunlight directly into electricity using solar panels;
- concentrated solar power (CSP) – a system that concentrates sunlight using mirrors or lenses to heat fluid and generate electricity through steam turbines;
- biomass – energy production from organic materials such as wood, agricultural waste, organic waste, or specially grown energy crops;
- geothermal – utilization of Earth's internal heat for electricity generation or heating supply;
- hydro – electricity production by harnessing water power, typically through dams or micro-hydroelectric plants;
- battery energy storage systems (BESS) – electricity storage technologies, typically in lithium-ion batteries, for subsequent use during peak demand or when RES generation decreases.

These indicators are not directly included in the RECAI calculation methodology, but are used to identify countries with high technological potential in specific renewable segments while having

deficiencies in other aspects of the investment climate. This allows for identifying market opportunities that may remain hidden when analyzing only the overall ranking [7].

2.1 Dataset

The empirical base of our study consisted of RECAI values and technology-specific scores (energy imperative, policy stability, project delivery, capital availability, natural resource diversity) for 2024 for the 40 most attractive countries for renewable energy investment worldwide: Argentina, Australia, Austria, Belgium, Brasil, Canada, Chile, China, Denmark, Egypt, Finland, France, Germany, Greece, India, Ireland, Israel, Italy, Japan, Kazakhstan, Mexico, Morocco, Netherlands, Norway, Peru, Philippines, Poland, Portugal, Romania, Saudi Arabia, South Africa, South Korea, Spain, Sweden, Switzerland, Taiwan, Turkey, UK, US, and Vietnam.

Numerical calculations were performed using Statistica software [16] based on indicator values published in the "62nd edition of the Renewable Energy Country Attractiveness Index" [7].

2.2 Method

General Regression Models (GRM) represent a comprehensive statistical framework designed to examine relationships between dependent and independent variables across diverse data structures and distributions. The primary purpose of these models extends beyond simple linear associations to accommodate complex, non-linear patterns while providing robust parameter estimation and hypothesis testing capabilities. This methodological approach proves particularly valuable when analyzing composite indices and their underlying components, as it enables the decomposition of multifaceted constructs into interpretable individual effects [17].

The basic mathematical formulation follows the general structure:

$$Y = f(X_1, X_2, ..., X_k) + \varepsilon, \quad (1)$$

where Y represents the dependent variable, X_1 through X_k denote independent variables, $f(\cdot)$ describes the functional relationship, and ε captures the error term.

For multiple linear regression applications, this translates to

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + ... + \beta_k X_k + \varepsilon, \quad (2)$$

where β coefficients represent parameter estimates quantifying the magnitude and direction of each predictor's influence.

The model estimation typically employs ordinary least squares methodology, minimizing the sum of squared residuals:

$$\Sigma(Y_i - \hat{Y}_i)^2, \quad (3)$$

where $\hat{Y}_i$ represents predicted values.

Model performance evaluation relies on metrics such as R-squared, adjusted R-squared, and various information criteria, while statistical significance testing of individual parameters utilizes *t*-statistics and corresponding p-values to assess the reliability of estimated relationships.

3 RESULTS AND DISCUSSION

Table 1 presents the results of applying the GRM method to analyze the relationship between RECAI and the analyzed technology-specific indices of renewable energy technologies. The obtained results demonstrate a statistically significant impact of most technological indices on the formation of the overall attractiveness of renewable energy markets.

Solar PV emerged as the dominant technological driver. This indicator shows the most powerful impact among all technologies with an unstandardized coefficient of 0.43 ($p < 0.001$) and the highest standardized coefficient of 0.42. This confirms the critical role of solar photovoltaics in determining countries' investment attractiveness. Onshore wind ranks second in terms of impact ($\beta = 0.34$, standardized $\beta = 0.32$, $p < 0.001$), demonstrating the stable significance of onshore wind energy as a key factor in market attractiveness.

Technologies Solar CSP, Offshore wind, and BESS exert a moderate influence. Despite the negative unstandardized coefficient (-0.04), Solar CSP has a positive standardized effect, which may indicate complex interactions with other model variables. Offshore wind ($\beta = 0.13$, $p < 0.001$) and BESS ($\beta = 0.18$, $p < 0.001$) show a moderate but statistically significant positive impact, reflecting the growing importance of offshore wind energy and energy storage systems.

Table 1: Model parameter estimates.

Sigma-restricted parameterization									
	RECAI Param	RECAI Str. Err	RECAI *t*	-95,00% Cnf. Lmt Raw	+95,00% Cnf. Lmt Raw	RECAI β	RECAI Str. Err β	-95,00% Cnf. Lmt β	+95,00% Cnf. Lmt β
Intercept	15.22	3.50	4.36	0.01	8.10	22.35			
Onshore wind	0.34	0.05	6.27	0.00	0.23	0.45	0.32	0.05	0.21
Offshore wind	0.13	0.03	3.94	0.00	0.06	0.19	0.28	0.07	0.14
Solar PV	0.43	0.08	5.32	0.00	0.27	0.60	0.41	0.08	0.25
Solar CSP	-0.04	0.05	-1.20	0.243	-0.12	0.03	-0.10	0.09	-0.28
Biomass	0.03	0.05	0.56	0.58	-0.07	0.13	0.04	0.07	-0.10
Geothermal	0.03	0.03	1.06	0.30	-0.03	0.09	0.06	0.05	-0.05
Hydro	-0.06	0.03	-1.88	0.07	-0.12	0.02	-0.10	0.05	-0.20
BESS	0.18	0.04	4.66	0.00	0.10	0.26	0.33	0.07	0.19

Table 2: Test of SS Whole Model vs. SS Residual.

Dependent Variable	Multiple R	Multiple R^2	Adjusted R^2	SS Model	df Model	MS Model	SS Resid.	df Resid.	MS Resid.	F	*p*
RECAI	0.97	0.94	0.93	1333.21	8	166.65	83.94	31	2.71	61.55	0.00

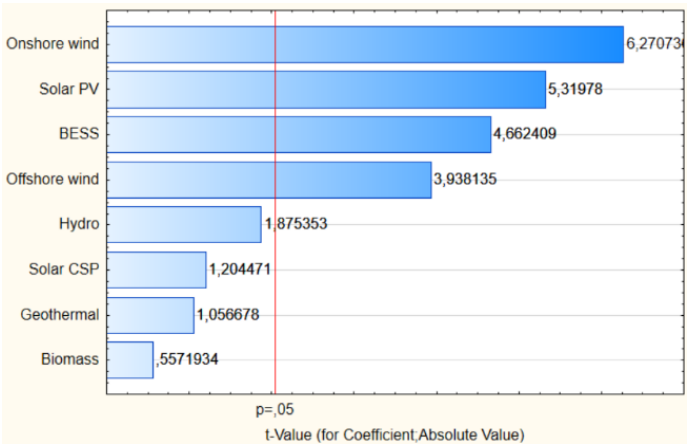


Figure 1: Pareto chart of t-values for coefficients.

Technologies with limited impact are Geothermal, Hydro, and Biomass. Geothermal energy demonstrates a statistically insignificant effect (p = 0.30), which is logically explained by its geographical specificity and limited resource availability. Hydro shows a weak negative impact (β = -0.06, p = 0.07), which may reflect the saturation of traditional hydroelectric capacity in developed countries or environmental constraints on new projects. Biomass has the smallest positive effect (β = 0.03, p = 0.59), remaining statistically insignificant, which may indicate limited investment interest in this technology at the global level.

Onshore wind, Solar PV, BESS, and Offshore wind have statistically significant coefficients (t_{emp} > t_{table}) even at the strict level α = 0.01. Hydro, Solar CSP, Geothermal, and Biomass do not achieve statistical significance (t_{emp} < t_{table}) at α = 0.05 (Fig. 1).

Table 2 presents the results of the multiple regression model.

Analysis of the regression model results demonstrates a differentiated impact of various renewable technologies on the formation of overall RECAI with high statistical significance for most predictors. The model reveals high explanatory power and statistical validity of the overall specification.

The F-statistic is 4.37 (p = 0.00), which confirms the statistical significance of the model as a whole and rejects the null hypothesis that there is no relationship

between the predictors and the dependent variable. This indicates that at least one of the technology-specific indices has a significant impact on RECAI.

Based on the results of the conducted analysis, we constructed an analytical model of RECAI dependence on key technological drivers (the regression equation includes only statistically significant predictors):

$$\begin{aligned} RECAI = 15.22 + 0.34 \times Onshore_wind + \\ + 0.431 \times Solar_PV + \\ + 0.13 \times Offshore_wind + 0.18 \times BESS. \end{aligned} \quad (4)$$

The constant (15.22) represents the baseline RECAI value in the absence of technological indices influence, reflecting the minimum level of renewable energy market attractiveness regardless of specific technological capabilities. The Solar PV coefficient (0.43) is the largest among all predictors. This confirms the dominant role of solar photovoltaics in forming investment attractiveness. The Onshore wind coefficient (0.34) indicates a strong positive impact of onshore wind energy, confirming the critical importance of wind resources. The BESS coefficient (0.18) demonstrates the growing role of energy storage systems in market attractiveness assessment, reflecting the importance of energy infrastructure for renewable energy integration. The Offshore wind coefficient (0.13) shows a moderate but significant impact of offshore wind energy, which may reflect the more limited geographical availability of this technology compared to onshore alternatives.

The exclusion of statistically insignificant variables (Solar CSP, Geothermal, Hydro, Biomass) improves model efficiency and provides more reliable RECAI forecasting through key technological drivers.

To visualize the relationships between the four influential technological predictors and the dependent variable RECAI, we constructed three-dimensional diagrams (Fig. 2-7).

The interdependency diagram of RECAI, Onshore wind, and Solar PV (Fig. 2) demonstrates a quite steep surface rise, reflecting the strong positive impact of both technologies on RECAI. The highest investment attractiveness values are achieved only with simultaneously high indicators of both technologies, indicating their synergistic impact on the renewable energy market attractiveness.

Fig. 3 shows a three-dimensional diagram visualizing the relationship between RECAI, Offshore wind, and BESS. A less steep rise is observed compared to the previous visualization, which corresponds to the smaller regression coefficients of these technologies. The lowest RECAI values are concentrated in the area of low indicators for both offshore wind energy and energy storage systems. Maximum values are achieved only with high indicators of both technologies, but the overall variation range is smaller compared to the main technologies.

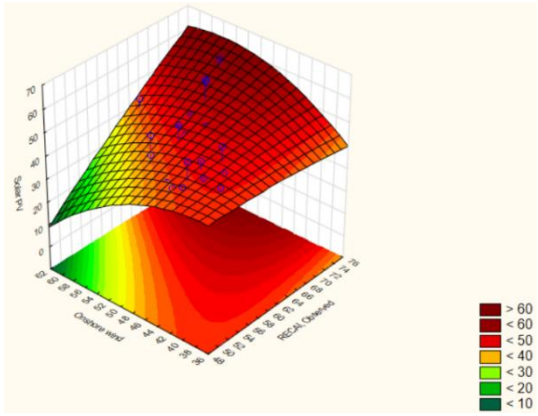


Figure 2: 3D Surface Plot of RECAI against Onshore wind and Solar PV.

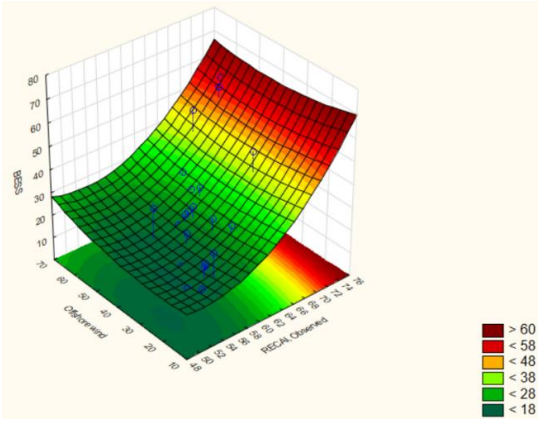


Figure 3: 3D Surface Plot of RECAI against Offshore wind and BESS.

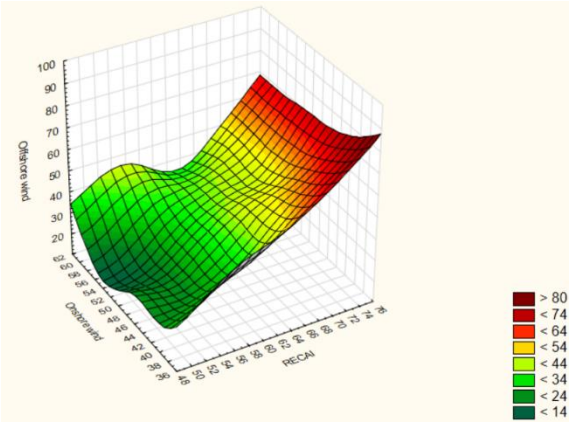


Figure 4: 3D Surface Plot of RECAI against Offshore wind and Onshore wind.

The diagram presented in Fig. 4 demonstrates a moderate synergistic effect between the two wind technologies. The surface has a smooth rise with a greater slope towards onshore wind energy, indicating its dominant influence on RECAI in this technology pair.

Fig. 5 shows an interaction diagram of energy storage systems with onshore wind energy. The surface demonstrates a uniform rise, where both technologies have approximately equal importance for forming high RECAI values, confirming their complementarity.

The 3D diagram shown in Fig. 6 displays a powerful synergistic effect between energy storage systems and solar photovoltaics. The surface has a steep rise, particularly pronounced in the Solar PV direction, which emphasizes the critical importance of this technology.

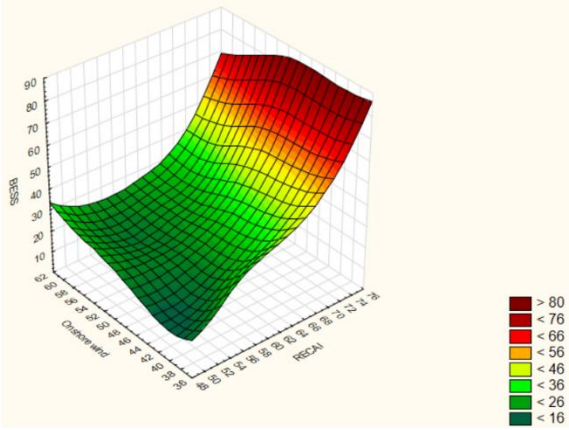


Figure 5: 3D Surface Plot of RECAI against BESS and Onshore wind

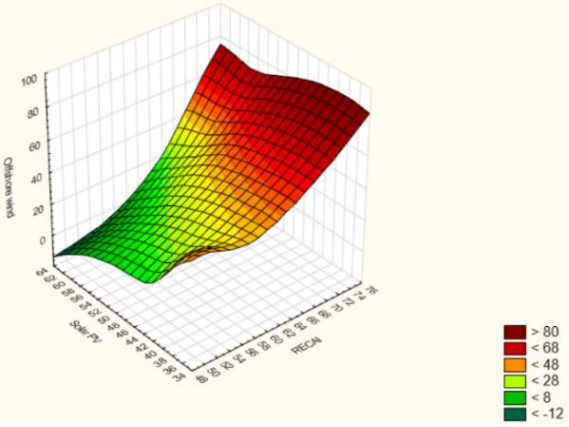


Figure 6: 3D Surface Plot of RECAI against Offshore wind and Solar PV.

The diagram presented in Fig. 7 demonstrates an asymmetric impact of technologies, where Solar PV has a significantly greater effect compared to offshore wind energy. The surface shows that solar energy is a key driver of high RECAI values in this combination.

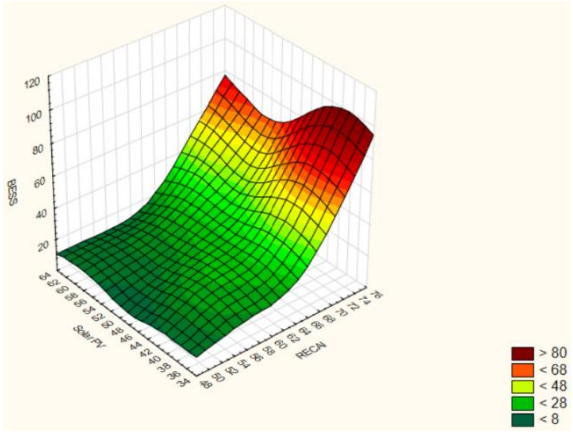


Figure 7: 3D Surface Plot of RECAI against BESS and Solar PV.

The results of the graphical analysis confirm the fundamental importance of synergistic development of renewable energy technologies for maximizing the investment attractiveness of markets, with Solar PV and Onshore wind acting as the most influential technologies, while Offshore wind and BESS play an important but supporting role in shaping overall market attractiveness.

5 CONCLUSIONS

The conducted study of the relationship between the Renewable Energy Country Attractiveness Index and technology-specific indices using General Regression Models allowed for the identification of key patterns in the formation of investment attractiveness of renewable energy markets and the identification of dominant technological drivers at the global level.

The results of the regression analysis demonstrate the differentiated impact of various renewable technologies on the overall attractiveness of markets. Solar PV and Onshore wind proved to be the most influential predictors with the highest statistically significant coefficients (0.43 and 0.34, respectively), confirming their critical role in shaping the investment climate. These technologies are characterized by the highest t-statistics (5.32 and 6.27), indicating the reliability of their impact on RECAI regardless of other factors.

BESS and Offshore wind demonstrated moderate but statistically significant positive impact on investment attractiveness with coefficients of 0.18 and 0.13 respectively. This reflects the growing importance of energy storage systems and offshore wind energy in the modern energy transition, although their impact is smaller compared to traditional renewable technologies.

The technologies Solar CSP, Geothermal, Hydro, and Biomass proved to be statistically insignificant predictors of RECAI, which can be explained by their geographical specificity, technological limitations, or saturation of corresponding markets. Particularly indicative is the insignificant impact of hydropower, which may reflect the depletion of traditional hydro resource potential in developed countries.

The three-dimensional visualization of relationships confirmed the synergistic nature of the impact of key technologies on RECAI, demonstrating that the highest levels of investment attractiveness are achieved with simultaneously high indicators of several renewable technologies. This emphasizes the importance of a diversified technological portfolio for maximizing market attractiveness.

The obtained results can provide relevant information to investors and policymakers regarding key technological drivers of investment attractiveness and contribute to the formation of more effective national renewable energy development strategies and optimization of investment portfolios in this sector.

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Implementation of a Gender Approach and Socially Oriented HR Branding Practices in the Business Engineering System: International Legal and Marketing Aspects in the Context of Digitalization

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Keywords: Corporate Sustainability, Digital Business Transformation, Employee Engagement, Gender Equity Indicators, Inclusive Labor Relations, International Labor Standards, Marketing Engineering, Responsible Employer Image, Social Innovation, Strategic HR Management.

Abstract: The purpose of this paper is to develop an interdisciplinary mechanism for implementing gender-sensitive and socially responsible HR branding within the business engineering system of modern companies. The study aims to integrate gender equality principles, international legal standards, and sustainable development criteria into corporate HR models in the context of digital transformation. The research is based on qualitative content analysis, comparative analysis of international practices, statistical examination of gender indicators (WEF, Eurostat, UN Women) and theoretical modeling. These methods enabled the authors to identify structural components of inclusive HR branding and design a multi-level framework for sustainable labor relations. The study systematizes key elements of gender-sensitive HR branding, develops a visualized model of sustainable employee-employer relations, and identifies critical gender disparities that influence HR decision-making. The findings demonstrate that integrating gender equality, CSR principles, and marketing engineering tools enhances workforce engagement, strengthens employer attractiveness, and improves organizational resilience. The paper offers a unified model that embeds gender indicators into HR branding and business engineering processes, providing an operational structure for transforming corporate governance in line with international legal and ethical standards. The results can be applied by companies to optimize recruitment, employee development, career management, and outplacement processes through gender-sensitive and socially responsible HR practices. The proposed mechanism supports evidence-based HR decisions and contributes to the formation of an inclusive and competitive employer brand.

1 INTRODUCTION

In the context of global digital transformation and the growing importance of ethical governance, the integration of gender-sensitive and socially responsible practices into human resource branding has emerged as a critical challenge and opportunity for modern organizations. As companies navigate the complexities of employer reputation, workforce sustainability, and stakeholder engagement, the alignment of HR strategies with gender equality principles and corporate social responsibility frameworks becomes not only a moral imperative but also a strategic necessity.

2 LITERATURE REVIEW

The study is positioned at the intersection of gender studies, human resource management, business engineering, and international law. It draws on diverse interdisciplinary sources to address the pressing need for inclusive and evidence-based HR models that promote long-term employee engagement, gender equity, and organizational resilience. Recent literature suggests divergent approaches to integrating gender dimensions in the workplace (from focusing on intersectionality and identity politics to embedding statistical indicators and legal norms within management systems) and this

diversity of perspectives reflects a wider debate on whether gender equality should be treated as a regulatory requirement or a voluntary ethical commitment.

3 RESEARCH METHODOLOGY

The methodological framework of this study integrates different scientific methods, each serving a specific research objective within the interdisciplinary examination of gender-sensitive and socially responsible HR branding. Qualitative content analysis was applied to systematize conceptual approaches to gender equality, CSR and HR branding and to reveal their intersections in the context of digital transformation. Comparative analysis enabled the assessment of international legal standards, cross-country gender disparities and corporate practices, thereby identifying structural differences and best practices relevant for integrating gender principles into business engineering systems. Statistical evaluation of gender indicators derived from WEF, Eurostat, UN Women and national datasets was used to quantify existing inequalities and substantiate the necessity of evidence-based HR decision-making. Theoretical modeling facilitated the development of a multi-level mechanism for structuring sustainable labor relations and operationalizing gender-sensitive HR branding within corporate governance frameworks. Together, these methods ensured a comprehensive and analytically grounded exploration of the research problem.

4 MECHANISM FOR IMPLEMENTING A GENDER APPROACH AND SOCIALLY ORIENTED HR BRANDING PRACTICES IN THE BUSINESS ENGINEERING SYSTEM

The analysis of sources dedicated to the gender approach is conceptually essential for providing a scholarly foundation for the study of inclusive practices in human resource management and employer branding, as they outline intercultural and intersectional dimensions of gender identity that enable the rethinking of corporate policies through the lens of social justice, equal access, and non-discrimination [1], [2].

The integration of social responsibility into business practices is a fundamental component of the sustainable development strategy of modern companies, particularly in the context of digital transformation, as it allows for a comprehensive understanding of the evolution of CSR approaches as a key element in risk management, corporate reputation and stakeholder trust [3], [4].

Research dedicated to employer branding represents contemporary concepts of human capital management as a strategic asset that directly influences a company's competitiveness in the digital age, allowing for the observation of the evolution of employer branding from traditional recruitment to a systemic strategy for shaping an attractive, responsible, and gender-sensitive employer image [5], [6].

The ability to integrate gender, ethical, and employer branding principles into the business engineering system requires an interdisciplinary approach, as confirmed by the analyzed works of contemporary researchers in this field. These studies highlight the potential of business engineering as a tool for structural transformation of organizations, enabling the effective implementation of socially responsible practices through digital solutions, business process re-engineering and marketing optimization [7]-[9].

The analysis of sources devoted to gender statistics and indicators, as well as international legal norms regulating gender issues in the labor sphere, is methodologically justified and critically important for building an evidence-based foundation for the study of socially responsible HR practices and the implementation of the gender approach within the business engineering system. The effective realization of an inclusive HR strategy depends on the use of valid, methodologically sound indicators that reveal not only formal but also structural barriers to resource access [10], [11].

4.1 Modelling of the Structure and Key Aspects of Forming Sustainable Corporate Relationships Within the Personnel Marketing System

In our opinion, the implementation of a gender approach and socially responsible HR branding practices within the business engineering system of a modern company should include the development of sustainable relationships in the corporate personnel marketing system and encompass the following key directions:

- the integration of visual models of structural components and the analysis of the features of forming long-term employment relationships under the conditions of digital transformation of corporate interactions;
- a multi-faceted characterization of sustainable employee relations as an intangible marketing asset, taking into account international legal norms and gender criteria;
- the development of a concept of the employee's professional life cycle in terms of the calendar duration of their life. The synchronization of this cycle with the internal life cycle of a specific company and the comprehensive set of its marketing efforts should form the foundation for an integrated impact aimed at creating and nurturing long-term relationships with employees as a strategically valuable marketing asset;
- the optimization of marketing processes for the formation and evolution of sustainable relationships between the company and its personnel in the context of digitalization and global competition for talent in the labor market;
- the study of the specifics of outplacement within the HR branding system aimed at maintaining long-term employment relationships with an emphasis on gender equality;
- the development of a methodological approach for the quantitative assessment of the effects arising from the development of strategic relationships between the company and its employees, considering international legal and marketing contexts.

The visual modeling of the structure and key aspects of forming sustainable corporate relationships within the personnel marketing system is presented in Figure 1. The initial level, which ensures the effectiveness of interaction between the company and the employee and creates the prerequisites for the long-term nature of their relationship, is the employee's performance of basic labor functions in exchange for agreed remuneration. It is important to note that, at this stage, the gender approach implies equal access to employment opportunities and a fair remuneration system for individuals of all genders.

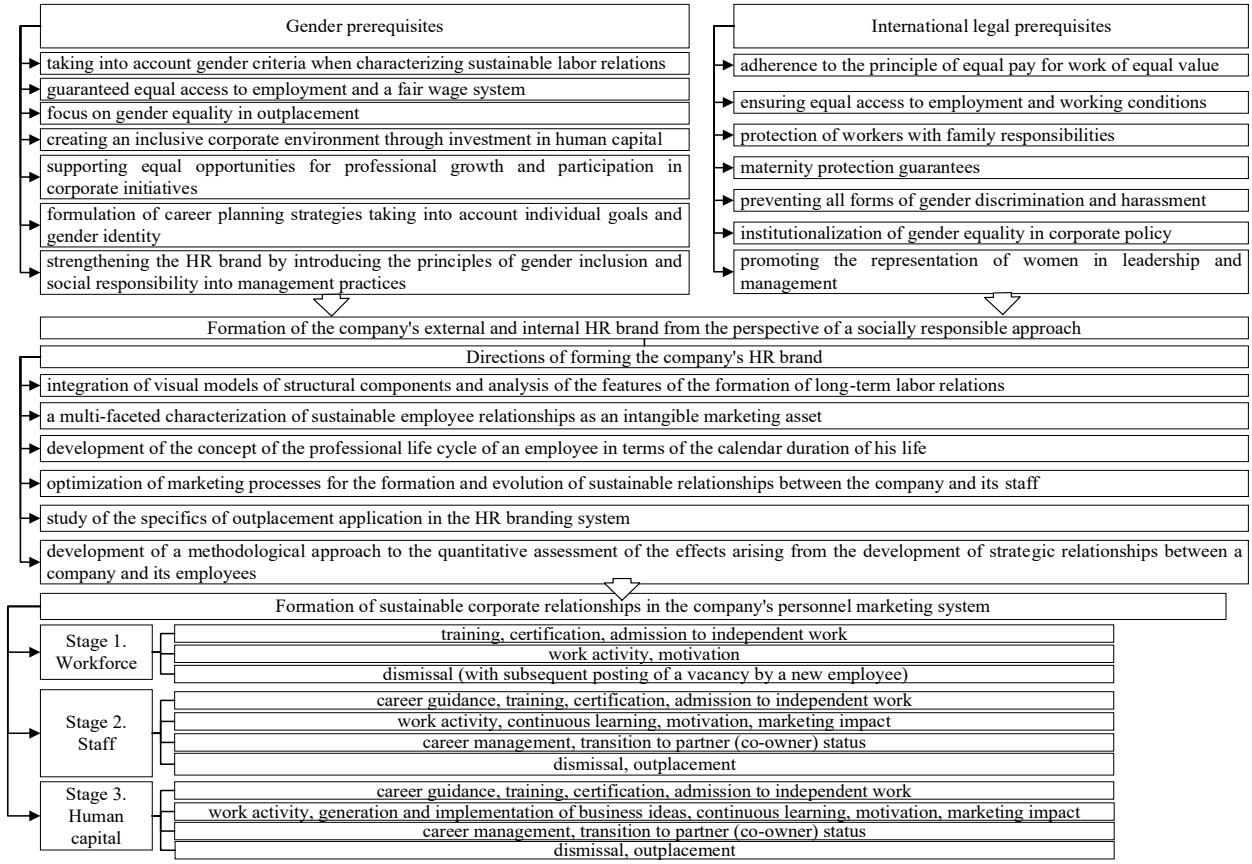


Figure 1: Mechanism for implementing a gender approach and socially responsible HR branding practices in the business engineering system.

4.2 Analysis of Gender Statistics and Indicators in the Context of Research on Socially Responsible HR Branding Practices in the Business Engineering System

Gender statistics and indicators are an integral part of the gender approach throughout the entire policy cycle. First, they provide information for the policymaking process and ensure that interventions address the different needs and priorities of women and men. Second, they measure changes in the relationships between women and men over time in a particular policy area, program, or activity, as well as changes in the status or position of women and men. Third, they are an essential component of monitoring and evaluating the implementation and outcomes of policies, programs, and projects. Thus, gender statistics are intended to "reflect differences and inequalities in the status of women and men in all areas of life" [12]. By providing evidence on gender equality and gender gaps in key areas, they help make gender inequality visible – which, in turn, can be used in designing policies aimed at eliminating the identified disparities. They help identify data relevant to the lives of women and men and to the key areas of policy development.

The Global Gender Gap Index [13] provides an annual assessment of the status and progression of gender parity across four fundamental domains (Economic Participation and Opportunity, Educational Attainment, Health and Survival, and Political Empowerment). Established in 2006, it remains the most enduring index for monitoring the long-term advancements of various economies in bridging these disparities.

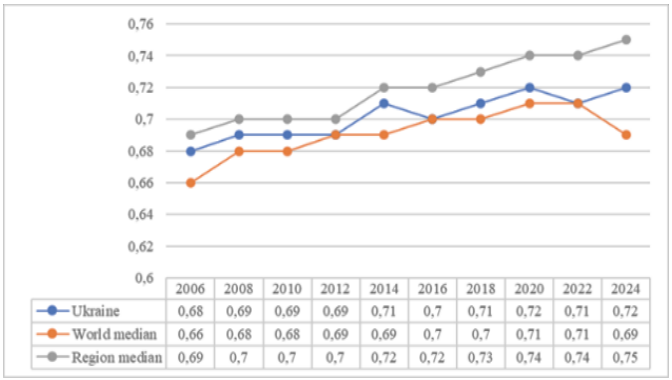
In 2024, the global gender gap index for all 146 countries analyzed in report indicates that 68.5% of the gap has been closed. Compared to the consistent sample of 143 countries assessed in the previous edition, the overall gender gap has narrowed by an additional 0.1 percentage point, increasing from 68.5% to 68.6%. Similarly, for the 101 countries that have been continuously monitored from 2006 to 2024, the gap has also improved by 0.1 percentage point, reaching a closure level of 68.6%.

European economies account for seven of the top ten positions in The Global Gender Gap Index ranking [13].

Ukraine's performance in the Global Gender Gap Index 2024 reflects a multifaceted trajectory of gender parity, characterized by notable advancements in educational attainment and economic participation yet hindered by persistent disparities in political representation. With an overall index score of 0.722 and a ranking of 63rd globally, Ukraine surpasses the global average of 0.685 but lags behind European counterparts, where the regional average is 0.750 (Fig. 2).

2024 represents a critical juncture for the Sustainable Development Goals (SDGs) and the trajectory of global development cooperation. With merely six years remaining until the 2030 target, the pace of progress - particularly in advancing gender equality - remains insufficient. The Summit of the Future, alongside the forthcoming thirtieth anniversary of the Beijing Declaration and Platform for Action, offers a vital opportunity to reaffirm international commitments to accelerating gender equality and the protection of women's rights.

The digital ecosystem continues to be predominantly shaped by young white men, with women remaining significantly underrepresented in the Information and Communications Technology (ICT) sector. Within the European Union, women constitute only 19% of ICT specialists, accounting for a mere 2% of total EU employment, in contrast to 7% for men (Fig. 3) [16].



	2006	2008	2010	2012	2014	2016	2018	2020	2022	2024
Ukraine	0,68	0,69	0,69	0,69	0,71	0,7	0,71	0,72	0,71	0,72
World median	0,66	0,68	0,68	0,69	0,69	0,7	0,7	0,71	0,71	0,69
Region median	0,69	0,7	0,7	0,7	0,72	0,72	0,73	0,74	0,74	0,75

Figure 2: Benchmark of Ukraine Global Gender Gap Index with world and region median, 2006-2024, score [13].

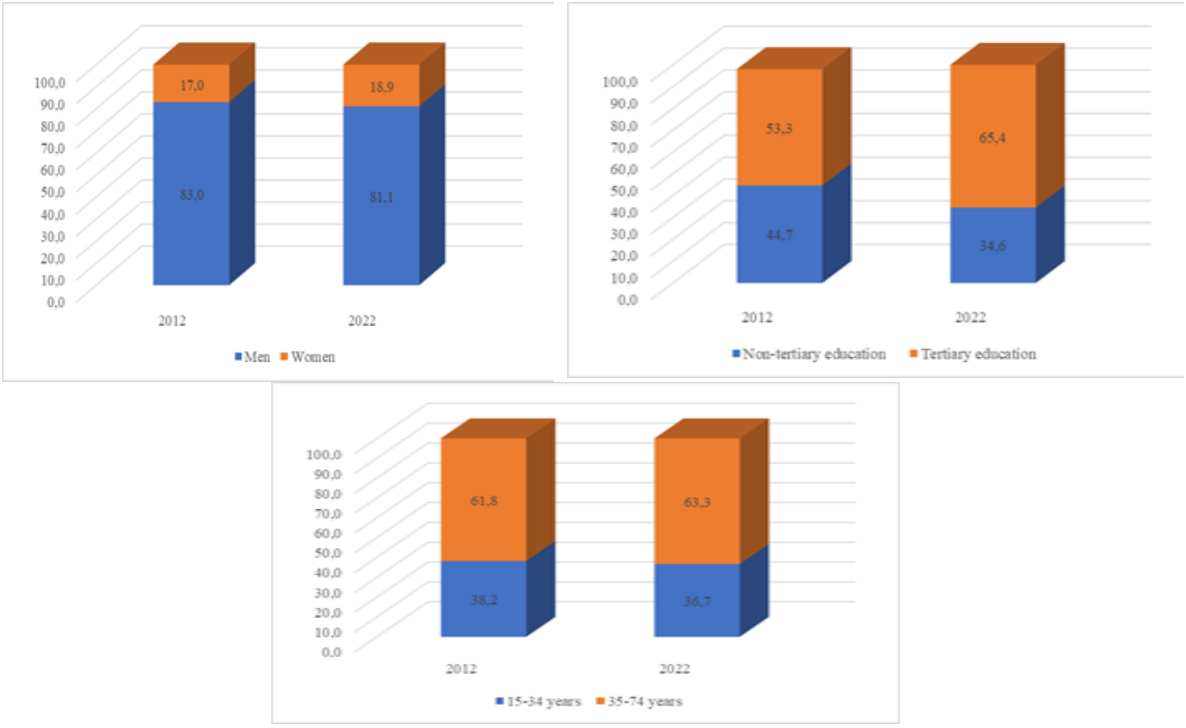


Figure 3: Distribution of persons employed as ICT specialists by sex, education attainment level and age, EU, 2012 and 2022, % [16].

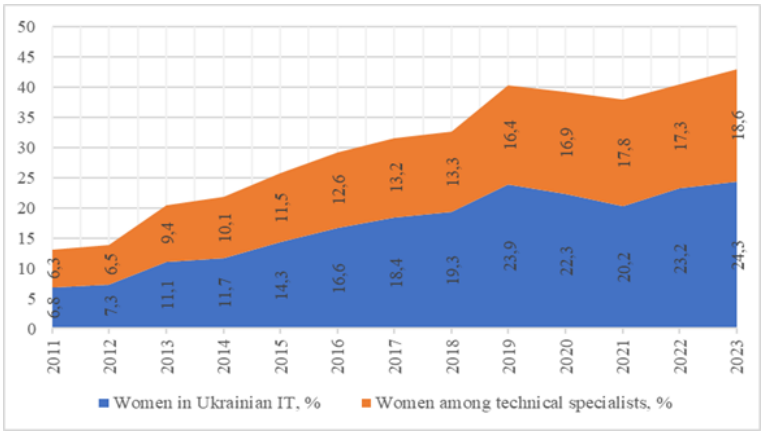


Figure 4: Dynamics of changes in the share of women in the Ukrainian IT sector, 2011-2023, % [14].

The representation of women in ICT varies across Central European nations, with Austria reporting 19%, Czechia 11%, Poland 17%, and Slovakia 15%. These figures may decline further when disaggregated to exclude non-technical roles such as human resources, marketing, and project management. Notably, women employed in ICT earn, on average, 19% less than their male counterparts, surpassing the EU-wide gender pay gap of 13%. In the Central European countries this wage disparity is even more pronounced, ranging between 20% and 30%.

The gender structure of Ukraine's IT industry demonstrates a steady trend toward increasing the share of women within the professional community. At the end of 2011, women's representation in the information technology sector did not exceed 7%. However, between 2012 and 2018, this figure gradually increased by several percentage points each year (Fig. 4) [14].

An analysis of the gender structure of employment in the Ukrainian IT sector reveals a stable trend toward the professional diversification of women across various fields within the industry. The highest level of female representation is observed in the field of quality assurance (QA engineers), accounting for 28% of all women in the industry, followed by software development, where 19% of women are employed. Overall, 66% of women work in technical roles, while 34% are engaged in non-technical specializations. This indicates a consistent pattern of gender-based professional segmentation since 2016, as the share of women in non-technical roles was lower prior to that period [14]. In our view, maintaining such a balance could serve as an indicator of the effectiveness of implementing a gender-sensitive approach in the HR policies of IT companies, contributing to equal opportunities for women in the high-tech sector. At the same time, it is already evident that there is a noticeably high level of corporate social responsibility in the field of IT product development, reflected in the growth of inclusive corporate environments. This enhances the attractiveness of companies to female professionals across different profiles and, in turn, supports the formation of a sustainable HR brand.

4.3 International Legal Aspects of Research on Socially Responsible HR Branding Practices in the Business Engineering System

The issue of gender equality in labor relations is of great importance and should encompass principles such as equal opportunities and equal treatment of men and women in employment, equal pay for equal work, improved work-life balance for employees, and equal treatment in hiring practices. At the current stage of economic development, men and women are formally equal in rights, yet the quality of employment remains unequal. Gender inequality in the labor market is, on the one hand, a consequence of social development, and on the other hand, one of the root causes of many problems that affect the functioning of the labor market [15]. Therefore, the gender approach is a vital component of comprehensive research into labor market issues, as it allows for the identification of mechanisms, causes, and consequences of gender inequality in employment.

For example, employment levels across EU countries vary significantly. In 2018, the highest levels of female employment were traditionally observed in Sweden (76.0%), the Netherlands (72.8%), Denmark (72.6%), Germany (72.1%), Lithuania (71.6%), Estonia (71.4%), and Finland (70.6%). The lowest levels were recorded in Italy (49.5%) and Greece (45.3%). Unemployment rates also differ significantly by gender. The largest gender disparities in unemployment were seen in Greece (24.2% for women versus 15.4% for men) and Spain (17.0% for women and 13.7% for men), where female unemployment exceeded male unemployment. Conversely, in Ireland and Lithuania, male unemployment was higher than female unemployment. Gender pay differentiation across the EU averages 16.1%, but gender pay gaps vary considerably among member states. While the gender pay gap has generally narrowed across the EU over the past decade, in some countries it continues to widen, despite improvements in women's employment levels, increased job opportunities, and higher education attainment. The largest gender pay gap is observed in Estonia (25.6%), while the smallest is in Romania (3.5%) [16].

According to the Global Gender Gap Report 2023, women make up approximately 47% of the global workforce. However, in many countries, women still face barriers to accessing equal opportunities. In Ukraine, the female employment rate increased to 51% in 2023, compared to 43% in 2021. Nonetheless, the gender pay gap widened, with women’s average earnings amounting to only 69% of men’s wages. In 2023, the global unemployment rate stood at 5.1%, with a projected increase to 5.2% in 2024, driven by labor market challenges in developed countries. The global gender pay gap also remains a significant issue: on average, women earn 20% less than men. In Europe, for instance, it is estimated that gender pay parity will take another 67 years to achieve, while in North America it will take 95 years. As of 2023, Ukraine's gender pay gap was 18.6%, but the government has set a target to reduce it to 13.6% by 2030 [17].

The uneven distribution can also be explained by the so-called compensation gap. Compared to other professions, women are more likely to accept jobs that are less physically demanding, have shorter work cycles, and offer certain social support (such as childcare). Women tend to have higher expectations regarding working conditions and benefits, but unlike men, they are generally less inclined to work overtime. Summarizing these factors, it is worth noting that women's human capital is considered to be lower than that of men. Therefore, according to human capital theory, the remuneration for women’s work tends to be lower than that for men’s work.

As for international organizations, they identify gender issues as one of the priorities of human development, which is reflected in their strategies. They also view gender equality as a resource for socio-economic development. Accordingly, the key features of international and European legislation aimed at eliminating gender discrimination and promoting the principle of equal treatment include: special measures to promote equality between women and men and prohibit direct and indirect discrimination; the prohibition of victimization, harassment, and sexual harassment; compensation for damages and sanctions for unlawful actions; the adoption of specific legislation on gender equality; the establishment of relevant institutions to protect both women and men; and the integration of the gender dimension into the formulation and implementation of public policy. The gender dimension plays an essential role in shaping and implementing public policy. The principles of gender equality and non-discrimination must be applied not only at the level of state governance but also across other levels. In particular, gender issues should be integrated into organizational policies, and appropriate procedures should be established to prevent discrimination and ensure equal access to resources and power for both women and men.

The ILO considers it extremely important to raise awareness of the legal aspects of gender equality in the world of work. Social and lasting peace can only be built on the foundation of social justice. This principle is proclaimed in the preamble to the ILO Constitution of 1919. Even at that time, immediately following World War I, the protection of women and the principles of equal remuneration for work of equal value were recognized as areas requiring urgent action. In 1944, the Declaration of Philadelphia was adopted at the International Labour Conference, and it is now an annex to the ILO Constitution. The declaration states that "all human beings, irrespective of race, creed or sex, have the right to pursue both their material well-being and their spiritual development in conditions of freedom and dignity, of economic security and equal opportunity." It further emphasizes that "poverty anywhere constitutes a danger to prosperity everywhere." The rights of working women are an integral part of the values, principles, and objectives that define the ILO's mandate, which is aimed at promoting social justice and decent work – fairly paid, productive employment carried out in conditions of freedom, equity, security, and dignity. Labor standards address the issue of gender equality in various ways. Some are gender-specific, explicitly calling for gender equality or the elimination of discrimination against women or men, such as the Equal Remuneration Convention (1951, No. 100), the Maternity Protection Convention (2000, No. 183), the Termination of Employment Convention (1982, No. 158), and the Employment Policy Convention (1964, No. 122). Other standards are gender-sensitive – their provisions take into account the needs of both women and men, even if not explicitly stated. Examples include the Workers with Family Responsibilities Convention (1981, No. 156), the Worst Forms of Child Labour Convention (1999, No. 182), the Part-Time Work Convention (1994, No. 175), the Home Work Convention (1996, No. 177), as well as several others that address working conditions such as safety, protection, and transportation. The fundamental Convention No. 111 encompasses both of these groups, as it is aimed at preventing discrimination and ensuring gender equality, while not being limited to gender discrimination alone. A third group of conventions contains technically neutral standards, which reveal gender-specific dimensions in practice – for example, in the collection and use of statistical data. These conventions cover issues such as wage payment, occupational accidents and injuries, working time, and social protection. The ILO has identified four conventions as key instruments for achieving gender equality in the world of work: the Equal Remuneration Convention (1951, No. 100); the Discrimination (Employment and Occupation) Convention (1958, No. 111); the Workers with Family Responsibilities Convention (1981, No. 156); and the Maternity Protection Convention (2000, No. 183) [18].

Focusing on the words of the ILO Director-General, Gilbert F. Houngbo, among the numerous challenges that persist is the fact that, on average, women still earn 20 percent less than their male colleagues. The central message of the 111th International Labour Conference, held on June 5, 2023, was reflected in his statement: "Social justice must be made a global priority" [19].

The agenda included a position on achieving equality between women and men in the workplace, which was at the core of the General Survey conducted by the Committee of Experts on the Application of Standards. As part of this review, the Committee of Experts' Report on the Application of Conventions and Recommendations was presented (Achieving gender equality at work). According to the document, over the past 25 years, the global momentum toward gender equality has grown at an unprecedented scale. The adoption of the Beijing Declaration in 1995 and its review in 2020 have

significantly increased interest in advancing gender equality [20].

In 2021, the United Nations Commission on the Status of Women called on governments to take action to eliminate the root causes of gender inequality and the barriers to women's full and equal participation. This was to be achieved through the expansion of women's economic opportunities and their right to work, the elimination of occupational segregation, and related measures.

The last century has been marked by tremendous progress for women, who in many countries have gained greater access to equal opportunities and improved treatment in the workplace. Women are increasingly entering sectors and leadership positions that were once considered "male-dominated." Maternity protection measures are becoming more widespread across many countries, and efforts are being made to support the balance between work and family responsibilities. The promotion of gender equality includes actions to ensure access and equality in education, training, and employment; the empowerment and economic autonomy of women; the prevention of violence and harassment, including gender-based violence such as domestic abuse and sexual harassment; maternity protection; and the advancement of women to leadership positions and their representation in government bodies [21].

5 CONCLUSIONS

Ensuring gender equality in labor relations is a key factor in shaping a socially responsible HR brand and developing sustainable business engineering models in the context of digital transformation. The gender approach in HR policy encompasses a wide range of objectives aimed at achieving equal rights and opportunities for women and men in the labor market, including the elimination of discrimination, the overcoming of gender stereotypes, the provision of equal pay for work of equal value, and the creation of conditions for balancing professional activities with family responsibilities.

The implementation of gender-sensitive strategies in HR management contributes to increased labor productivity, the strengthening of corporate culture, the formation of long-term employment relationships, and the enhancement of employer reputation. Priority areas in this field include ensuring equal access to employment and career advancement, introducing transparent pay mechanisms based on the principle of equal remuneration, developing flexible forms of employment, supporting parenthood, preventing sexual harassment, promoting women's leadership, and ensuring gender balance in senior management bodies.

Thus, adherence to gender equality principles and the implementation of socially responsible HR practices are not only an ethical imperative but also a strategic necessity for organizations striving for sustainable development, innovation, and compliance with international legal standards. The systemic integration of the gender approach into HR branding ensures the creation of an inclusive corporate environment and enhances business competitiveness at both national and international levels.

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The Impact of Artificial Intelligence on Managing Energy Infrastructure Development in the Age of Global Digital Transformation

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Keywords: Artificial Intelligence, Energy Infrastructure Development, Smart Energy Systems, Digital Energy Transformation, Critical Energy Infrastructure, Cybersecurity, Cyber-Resilience, Sustainable Energy Development, Energy System Resilience, Decision Support Systems, Machine Learning, Digital Twins, Sustainable Development.

Abstract: The article is devoted to the study of the development of scientific discourse on the application of artificial intelligence (AI) technologies in managing the development of energy infrastructure in the context of global digital transformation and the transition to low-carbon energy systems. The aim of the work is to identify the dynamics of publication activity, key thematic priorities and international scientific clusters based on the results of bibliometric analysis of publications indexed in the Scopus database for the period 2000–2025. The results obtained showed a rapid growth in scientific interest after 2020, which correlates with the development of Smart Grid, IoT, machine learning, predictive analytics technologies, as well as with the growing need to increase the resilience and cybersecurity of critical energy infrastructure. It was determined that the greatest intensity of research is observed in India, China, the USA, as well as in a number of European countries, which indicates the global nature of the topic. Semantic analysis of keywords allowed us to identify the dominant areas of scientific research: optimization of energy consumption and integration of renewable energy sources, development of intelligent energy grids and "smart" cities, implementation of digital twins of energy systems, use of forecasting algorithms and decision support. Based on the results, the conclusion was formulated that AI is becoming a strategic tool for the energy transition, ensuring increased energy efficiency, accuracy of network balancing, acceleration of response to emergencies, strengthening cybersecurity and achieving the Sustainable Development Goals. Practical recommendations include the development of standards for the use of AI in critical infrastructure, the creation of national energy data platforms and digital twins, strengthening institutional interaction between governments, businesses and scientific institutions, as well as the development of ethical and regulatory frameworks for the use of AI.

1 INTRODUCTION

In a rapidly digitalizing global economy, energy infrastructure remains a fundamental condition for the stability, competitiveness, and national security of states. The growth of technogenic complexity, the decentralization of energy generation, the development of renewable energy sources, and the growth of cyber threats make energy systems increasingly interdependent and vulnerable. According to analysts from Markets and Markets [1], the vulnerability of critical infrastructures stimulates the steady growth of the global cyber defense market: in 2020-2030 it will increase by 11.5%, to over 24 billion dollars. This emphasizes the urgent need to increase the cyber resilience of the energy sector as a strategic prerequisite for the sustainable functioning of the economy. In such conditions, traditional mechanisms for planning and modernization of energy systems are gradually losing their effectiveness, as they are unable to process large

data sets, integrate decentralized generation, and provide high forecasting accuracy [2]-[6].

Therefore, artificial intelligence (AI) is becoming a key tool for managing energy infrastructure in the era of digital transformation [7]-[11]. According to Statista [12], the global AI market has grown from 93.3 billion dollars in 2020 to 184 billion dollars in 2024, almost doubling. S. Ghimire's forecast [13] indicates that by 2027 the market volume will exceed 407 billion dollars.

International surveys confirm the public and institutional demand for the implementation of AI in the management of critical infrastructure facilities. According to a German study in 2022, 46% of citizens consider AI to be an effective tool for increasing the resilience of energy and transport systems to natural disasters [14]. At the same time, 41% of respondents fear the negative impact of algorithmic systems on the security of critical facilities, and 15% express a high level of concern about potential risks [15]. This demonstrates the ambivalence of the perception of intelligent technologies and the need to improve risk management policies.

According to the Center for Security and Emerging Technologies at Georgetown University [16], the integration of artificial intelligence into critical sectors creates both new opportunities for increasing efficiency and predictability, as well as new vulnerabilities associated with cyber risks and the human factor. At the same time, 81% of technology company executives predict that the use of advanced artificial intelligence models will provide at least a 25% increase in operational efficiency in the next three years, in particular in the area of load management, demand forecasting and optimization of renewable energy generation [17].

In the corporate sector, artificial intelligence is increasingly being used as a tool to improve productivity. According to a Celonis survey [18], 48% of companies identified automation and process optimization as the main motivation for implementing artificial intelligence. In the field of energy infrastructure development, this means moving to new models of asset management, monitoring of technical condition, forecasting of emergency situations and reducing energy losses [19]-[21].

The integration of artificial intelligence acquires special importance in the context of national and energy security. According to the conclusions of D. Araya and M. King [22], artificial intelligence forms a new architecture of defense and infrastructure systems, combining data analysis, autonomous technologies, neuromorphic computing and integration with IoT. This creates a large-scale potential for increasing the resilience of the energy sector, while at the same time generating the need for global risk regulation and standardization of algorithmic solutions [23]-[25].

Therefore, the study of the impact of artificial intelligence on the management of energy infrastructure development is a priority area of scientific research. It allows you to form the scientific foundations of effective digital transformation, increase energy sustainability and security, minimize risks, and implement sustainable development goals.

2 LITERATURE REVIEW

The analysis of modern scientific publications shows the increasing scientific interest in the relationship between artificial intelligence and critical infrastructure development management. Researchers K. Chen, X. Zhou, Z. Bao, M. J. Skibniewski and W. Fang [24] summarized the areas of application of artificial intelligence in infrastructure construction, highlighting the dominance of machine learning, computer vision and natural language processing technologies.

C. Sambucci and C. Paraschiv [25] identified the spectrum of cyber threats for artificial intelligence systems in critical sectors and proposed the concept of security auditing of AI models. Scientists H. Jing, W. Wei, C. Zhou and X. He [26] developed a system framework for artificial intelligence security, covering the stages of the life cycle from design to operation.

Japanese scientists T. Takeda, J. Kawamura, T. Murakami, T. Matsumura and A. Arai [27] focused on the gaps in the legal regulation of the use of artificial intelligence in water infrastructure. At the same time, J. J. Reddy, A. Mittal, V. Reddy and H. Das [28] proved the potential of combining artificial intelligence, blockchain and IoT to form sustainable "smart" infrastructures.

Summarizing the results, it can be stated that modern research forms three leading scientific directions:

1) security and reliability of artificial intelligence systems;
2) institutional management and legal support for their integration into critical infrastructure;

3) the transformative role of artificial intelligence in creating sustainable and digitally adaptive infrastructures.

The generalization of scientific achievements shows that research in the field of the impact of artificial intelligence technologies on the management of the development of critical infrastructure is gradually moving into the phase of sectoral specification. One of the priority and extremely important areas has become the management of energy infrastructure development, where artificial intelligence is considered not only as a technological tool, but as an integrative mechanism for the transformation of energy systems [29-34], combining digitalization, decentralization, security and resilience.

Scientific research by M. Ashok, K. Ganesan, R. Saravanan and R. Kumar [35] demonstrates that artificial intelligence algorithms provide systemic management of the balance between energy production, distribution and consumption, increasing the efficiency of network processes and reducing losses in energy systems.

Research by V. Pavlenko et al. [36] emphasizes the synergy between AI, blockchain and smart grids, which creates the basis for the formation of decentralized energy ecosystems with transparent management of data flows and energy resources.

B. Hanna, G. Xu, X. Wang, J. Hossain [37] emphasize that the potential of artificial intelligence is crucial for achieving the seventh goal of sustainable development, as it contributes to increasing energy efficiency, equitable energy access and the development of "clean" technologies.

The conceptual principles of integrating artificial intelligence into the energy sector are systematized in the work of A. M. S. Derbali [38], where the author considers artificial intelligence as the core of a future energy ecosystem capable of ensuring climate neutrality and maintaining energy balance in the face of technological variability.

The analysis of P. Arévalo & F. Jurado [39] shows that artificial intelligence is becoming a key factor in the optimization of distributed energy systems – from demand forecasting to the integration of renewable sources, ensuring the adaptability and flexibility of "smart" networks.

The studies of C. Biswas, A. Chakraborti, S. Majumder [40] present a wide range of methods (from neural networks to fuzzy logic systems) that provide predictive management and technical diagnostics in renewable energy.

A significant contribution to the formation of the theoretical basis was made by the work of B. Zohuri, F. Mossavar-Rahmani and F. Behgounia [41], where the concept of Business Resilience System (BRS) was proposed, which integrates elements of machine and deep learning to predict energy processes and increase the systemic resilience of energy markets.

Taken together, the results of the analysis allow us to state the emergence of a new scientific direction – AI-driven energy infrastructure management, which combines intelligent decision support systems, big data analytics, digital twins and cyber-physical energy models. Unlike previous studies of critical infrastructure development, which mostly emphasized protection and risks, the energy discourse focuses on innovation, sustainability and climate neutrality, identifying artificial intelligence as a strategic driver of the transition to a new architectonics of energy systems.

In view of this, the aim of the article is to theoretically substantiate and systematize the areas of influence of artificial intelligence on the management of energy infrastructure development in the era of global digital transformation; to identify the potential, risks and mechanisms for using intelligent technologies in ensuring energy security and increasing the efficiency of energy systems.

3 METHODOLOGY

The methodological basis of the study combines systemic, comparative-institutional, analytical and bibliometric approaches, which in combination provide a comprehensive assessment of the impact of artificial intelligence technologies on the management of energy infrastructure development in the context of global digital transformation.

The theoretical basis of the study is the system paradigm, according to which energy infrastructure is considered a complex socio-economic and technical system in which technological, institutional and managerial subsystems interact. This approach makes it possible to identify feedback loops, adaptive mechanisms and dependencies that determine the efficiency and resilience of the energy system under the influence of digital technologies and artificial intelligence algorithms.

The comparative-institutional approach was used to analyze models of integration of artificial intelligence technologies into the practice of energy system management of different countries and organizations (based on materials from the IEA, IRENA, WEF, and the European Commission). This allowed us to identify effective management models,

state regulation tools and organizational mechanisms that can be adapted to the Ukrainian energy context.

The empirical part of the study is based on quantitative and qualitative analysis of international data and scientific publications. The information base was formed on the basis of reports of leading international organizations – the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), the World Economic Forum (WEF) and the European Commission. These sources contain current indicators of the level of digitalization of the energy sector, the effectiveness of the use of artificial intelligence technologies, the dynamics of reducing operating costs and increasing the accuracy of demand forecasting.

In order to identify scientific trends and conceptual structures, a bibliometric analysis was conducted using the Scopus database as the main source of scientific information. The search query "Artificial Intelligence" and "Energy Infrastructure Development Management" covered publications for the years 2000-2025, with a detailed analysis carried out for the period 2013-2025, which is characterized by the highest scientific activity.

VOSviewer v.1.6.19 software was used to process and visualize the results, which allows building maps of keyword co-occurrence, co-authorship networks and citations. This made it possible to identify dominant scientific clusters, identify influential authors and trace interdisciplinary connections between the topics of artificial intelligence, energy efficiency and digital management.

Integration of the results of bibliometric, comparative and system analyzes made it possible to carry out a system-analytical synthesis aimed at identifying key determinants that shape the impact of artificial intelligence on the development of energy infrastructure.

The proposed methodological approach ensures the objectivity, reproducibility, and scientific validity of the research results, creating a basis for forming strategic management decisions to increase the efficiency, adaptability, and resilience of energy infrastructure in the context of digitalization.

4 RESULTS

A search of the Scopus database using the keywords "Artificial Intelligence" and "Energy Infrastructure Development Management" revealed 453 documents published between 2000 and 2025. The dynamics of scientific papers demonstrate a significant increase in publications after 2018 (Fig. 1), reflecting the rapid digital transformation of the energy sector, the introduction of 5G–6G technologies, the active development of "green" energy concepts, and the strengthening of global sustainable development programs.

Until the mid-2010s, the number of papers remained insignificant, but after 2020 there has been a sharp acceleration with peak indicators in 2024-2025, which confirms the sharp increase in the relevance of research on the application of artificial intelligence in energy infrastructure management.

Calculations showed an exponential growth of scientific interest: the average annual growth rate (CAGR) was 21.7%, and the period for doubling the number of publications was about 3.2 years. The peak of activity in 2024-2025 (+139%) correlates with the strategic initiatives of the EU and the IEA, in particular the Digital Energy Action Plan 2022-2025 and AI for Energy Transition. The value of the coefficient of determination of the model (R^2=0.52) indicates that more than half of the variation in the dynamics of publications is explained by the exponential trend, typical of rapidly growing interdisciplinary areas.

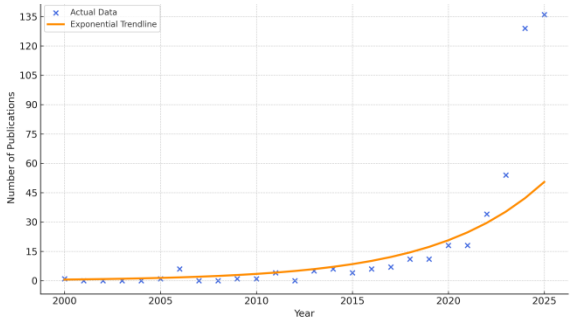


Figure 1: Exponential growth of publications on "AI in energy infrastructure development management" (2000-2025).

The evolution of the publication flow allows us to identify four stages of the development of scientific interest (Fig. 2): the period of emergence (2000-2010) with isolated works; the period of formation (2011-2017) with a gradual increase in applied research on machine learning in energy; the period of active development (2018-2021), when the integration of AI is associated with the concepts of Industry 4.0, Smart Grid and IoT; the period of intensive expansion (2022-2025), within which sustainable scientific schools were formed in the USA, India, China and the EU.

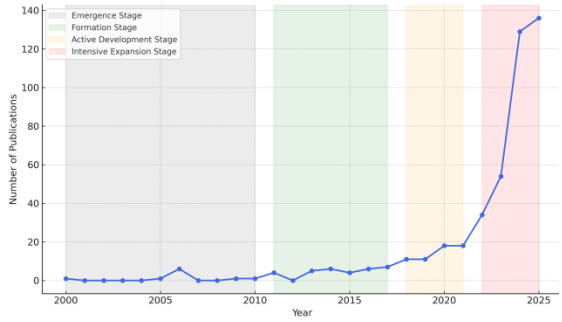


Figure 2: Stages of scientific interest in AI-driven energy infrastructure development management.

The most cited publications (Table 1) focus on the intersection of artificial intelligence, energy efficiency, digital management technologies and sustainable development. Field-Weighted Citation Impact (FWCI) indicators range from 1.84 to 16.11, which is 2-8 times higher than the industry average, confirming the high level of innovativeness of research.

Table 1: Most cited publications on "Artificial Intelligence in Energy Infrastructure Development Management" (Scopus, 2000-2025) [42]-[48].

Author(s), Year	Article Title	Source	Citations	FWCI	Core Subject / Scientific Focus
H. Yang et al. (2020) [42]	Artificial-Intelligence-Enabled Intelligent 6G Networks	IEEE Network	428	15.80	AI-based 6G network architectures; intelligent resource management; energy-efficient communication systems
A. Sun & B. Scanlon (2019) [43]	How can Big Data and machine learning benefit environment and water management	Environmental Research Letters	409	4.28	Big Data and ML for environmental and water resource monitoring; predictive analytics for sustainability
J.-P. Correa-Baena et al. (2018) [44]	Accelerating Materials Development via Automation, Machine Learning, and High-Performance Computing	Joule	277	1.84	Machine learning and automation in materials science; high-performance computing for energy materials
B. J. Singhet al. (2023) [45]	A systematic review of industrial wastewater management: Evaluating challenges and enablers	Journal of Environmental Management	260	9.01	Environmental management of industrial water systems; circular economy; sustainable development
S. Bruno et al. (2018) [46]	Historic Building Information Modelling: performance assessment for diagnosis-aided information modelling and management	Automation in Construction	243	3.29	BIM/HBIM for infrastructure management; cognitive automation and diagnostic modelling
B. Mao et al. (2022) [47]	AI Models for Green Communications Towards 6G	IEEE Communications Surveys and Tutorials	220	16.11	AI models for green communications; energy-efficient 6G networks; ML/DL in network management
Y.-H. Lin & M.-S. Tsai (2014) [48]	Development of an improved time-frequency analysis-based nonintrusive load monitor for load demand identification	IEEE Transactions on Instrumentation and Measurement	163	4.94	Non-intrusive load monitoring (NILM); smart grid applications; load optimization algorithms

Several leading research areas were identified (Table 2): AI in Smart Grid networks and 6G communications; intelligent energy resource monitoring and management systems; application of Big Data and machine learning in the water-energy nexus; automation of materials science and energy technology processes; and integration of AI in ensuring the sustainable development of industrial systems.

Table 2: Leading Scientific Publication Outlets on "Artificial Intelligence in Energy Infrastructure Development and Management" (Scopus, 2000–2025).

Journal / Book Series (Publisher)	Source Type	Scopus Coverage Years	Subject Areas	CiteScore 2024	SJR 2024	SNIP 2024	Core Scientific Focus
Energies (MDPI)	Open Access Journal	2008-2025	Energy Engineering, Renewable Energy, Electrical and Electronic Engineering, Sustainability	7.3	0.713	1.027	Digitalisation of energy systems; intelligent grid management; decarbonisation and energy efficiency
Lecture Notes in Networks and Systems (Springer Nature)	Book Series	2016-2025	Control and Systems Engineering, Signal Processing, Computer Networks	1.0	0.166	0.233	Networked systems; modelling of cyber-physical infrastructures; AI-based process control
IEEE Access (IEEE)	Open Access Journal	2013-2025	Engineering (General), Computer Science, Materials Science	9.0	0.849	1.504	Applied machine learning; energy consumption forecasting; Smart Grid AI models
Sustainability (Switzerland) (MDPI)	Open Access Journal	2009-2025	Environmental Science, Energy, Computer Science, Geography & Planning	7.7	0.688	1.113	Sustainable development policy; energy transition; socio-economic assessment of AI impacts
Lecture Notes in Computer Science (Springer Nature)	Open Access Book Series	1973-2026	Theoretical & Applied Computer Science	2.4	0.352	0.555	Algorithmic approaches; machine learning; big data processing in technical systems
Studies in Systems, Decision and Control (Springer Nature)	Book Series	2014-2025	Decision Sciences, Control & Systems Engineering, Economics	1.5	0.116	0.000	Decision-making theory; infrastructure risk management; AI in control systems
Sustainable Civil Infrastructures (Springer Nature)	Book Series	2018-2025	Civil & Structural Engineering, Environmental Engineering	0.3	0.140	0.108	Sustainable infrastructure technologies; energy-efficient engineering solutions; digital modelling

The leading publishers in the research topic are MDPI, Springer Nature and IEEE (Table 3), which generate more than 70% of the analyzed publications. The Energies and Sustainability journals (MDPI) are characterized by high CiteScore (>7) and SNIP (>1.0), IEEE Access demonstrates one of the highest citation rates (CiteScore=9.0, SNIP=1.504), and the Springer series (Lecture Notes in Networks and Systems, Studies in Systems, Decision and Control) dominate the segment of algorithmic methods and digital technologies for energy systems management. The geography of publications indicates the formation of a global scientific network. The largest number of documents was prepared by researchers from India (106), China (52), the USA (50), the UK (24), Italy (23) and Australia (22). Ukraine (12 documents), Germany, South Korea, Ireland and Canada also provide significant contributions.

The analysis of scientific collaboration revealed several stable clusters (Fig. 3), which form a global network of research on artificial intelligence in energy infrastructure management. Each cluster has its own institutional core, research focus and thematic dominants, reflecting the socio-economic and technological priorities of the respective regions. The first is the Indian-Asian cluster, the core of which is India. The key participants are Saudi Arabia, the UAE, Egypt, Iraq, Taiwan and Nigeria. The cluster is characterized by a high intensity of inter-university collaborations, in particular between the Indian Institutes of Technology, the National Institutes of Technology, Sharda University, Lovely Professional University and a number of technical universities in the Middle East.

The main focus of research is related to the optimization of energy network management, renewable energy, the integration of solar and wind power plants into national energy systems, load forecasting and the application of machine learning for electric power Smart Grid platforms. A feature of this cluster is its focus on practical engineering solutions that are scalable in rapidly developing countries, and significant government investment in energy technologies as part of national energy security strategies.

Table 3: Thematic Clusters of Key Research Concepts on "Artificial Intelligence in Energy Infrastructure Development Management" (Scopus, 2000–2025).

Cluster Name	Dominant Keywords	Scientific Focus	Features
AI and Sustainable Resource Management	artificial intelligence, machine learning, optimization, decision support systems, water management, waste management, circular economy, carbon emission	Application of AI and ML for natural resource governance, optimisation of water supply and treatment, reduction of CO_2 emissions, and the development of circular economy models	Formation of intelligent environmental management ecosystems and advancement of the "green AI" concept in the context of SDG 7, SDG 9, SDG 11, SDG 13
Intelligent Energy Systems	smart grid, energy management, renewable energy, energy storage, demand side management, electric vehicle, cyber security, learning systems	AI-based energy governance: demand-side management, load forecasting, network security and renewable energy integration	Combination of technical (Smart Grids, IoT) and managerial (decision support, predictive analytics) approaches within AI-driven energy system control
Information Management and Data Analytics	information management, data analytics, IoT, blockchain, cloud computing, big data, decision making, learning algorithms	Digital analytics and data governance: IoT and Big Data for monitoring, blockchain platforms for energy transactions, cloud computing for analytics applications	Forms the technological core of digital energy systems, linking analytical models with risk management and cybersecurity
Digital Infrastructure and Next-Generation Communications	cloud-computing, 5G, 6G, network architecture, network security, smart infrastructure, real-time systems	AI-based management of next-generation communication and infrastructure systems: 5G/6G networks, real-time systems, and energy-efficient telecommunications	Development of AI-driven communication networks supporting intelligent energy platforms
Urban Energy and Sustainable Urbanism	smart city, urban growth, urban transportation, autonomous vehicles, planning, environmental management systems, sustainable city	AI for urban energy and infrastructure planning, optimisation of transportation and smart mobility, and development of sustainable cities	Integration of Smart City and Sustainable Urban Development concepts enabled by artificial intelligence

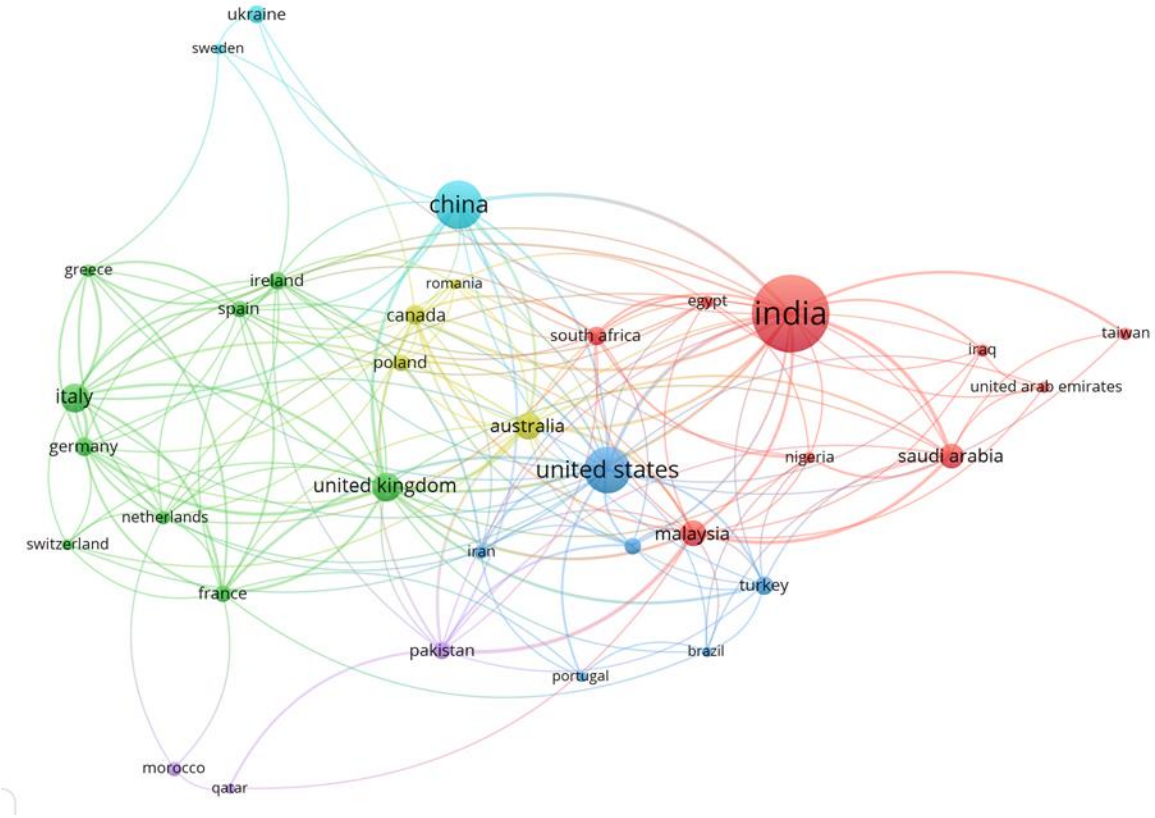


Figure 3: Identified clusters of international research collaboration on the selected topic.

The second is the Anglo-American cluster, which is formed by the USA, the UK, Australia, Malaysia, Turkey and partly Brazil, Portugal and Iran. Its research focuses on creating AI-based decision-making systems, predictive analytics and machine learning for load management and preventing accidents in energy networks. Significant attention is paid to green communication networks, the use of 5G–6G technologies, energy cybersecurity and protecting infrastructure from cyberattacks.

Leading organizations in the cluster include the Massachusetts Institute of Technology, the National Renewable Energy Laboratory (NREL), the University of Oxford, Imperial College London, the University of California and the University of Melbourne. The cluster is dominated by publications in highly ranked IEEE and Springer journals, which is due to the high level of algorithmic and analytical research.

The third is the European cluster, which unites research centers in the UK, Italy, Germany, France, Spain, the Netherlands, Ireland, Switzerland and Greece. Its distinctive feature is the close integration of EU environmental and energy policies with digital technologies for power system management. The cluster demonstrates the highest density of internal collaboration, reflecting the joint research programs Horizon 2020, Horizon Europe, Digital Europe, Green Deal and the institutional role of ACER-CEER in shaping regulatory approaches. The thematic focus covers modelling of sustainable energy transition, risk management and the development of Smart Cities/Smart Regions, digital twins of infrastructures, as well as the impact of AI on the decarbonization of industrial systems.

The fourth is the North African and Middle Eastern cluster, which includes Qatar, Morocco and partly Romania, which is in a transitional position. The main specificity of this cluster is related to the climatic vulnerability of the territories and the need for digital control of energy systems in conditions of increased risks associated with water scarcity, record temperatures and growing demand for electricity. Research focuses on the integration of renewable energy sources, optimization of energy generation and storage, as well as the use of artificial intelligence to reduce losses in networks and manage energy security.The fifth is the Chinese cluster, in which China acts as a coordinating center, supporting cooperation with Canada, Poland,

Ukraine and Romania. Research is focused on AI-driven Smart Grid systems, energy distribution optimization, energy storage development, and the creation of cyber-physical systems in the energy sector. There is a high participation of large industrial corporations and public-private research alliances, which reflects the strategic state programs of the energy transition in China. Ukraine, although playing a peripheral role, is an integrated part of this cluster, which creates opportunities for deepening international scientific cooperation in the field of digital energy. Thus, intercontinental ties formed between India, the USA, the UK, China and the EU countries form the core of the global research space. It is in this field that key concepts for the application of artificial intelligence in energy infrastructure management are generated, in particular in the areas of sustainable development, decarbonization, cybersecurity and intelligent modernization of energy networks.

In the analyzed sample, the most active donors of scientific projects were the National Natural Science Foundation of China (11 documents), European Commission (9), U.S. Department of Energy (7), UK Research and Innovation (5), Horizon 2020 Framework Program (4). An important element of Ukraine's integration into the international research space is support from the National Research Foundation of Ukraine.

The typological structure of documents indicates the dominance of conference proceedings (31.8%), scientific articles in peer-reviewed journals (28.3%), chapters in collective monographs (16.8%) and review publications (13.5%). This distribution indicates that the industry is in a phase of active formation, within which theoretical concepts are transformed into applied solutions and technological models.

According to Scopus classification, the research profile covers Engineering (53%), Computer Science (48%), Energy (27%), Environmental Science (21%), Social Sciences (15%), Business, Management and Accounting (9%), Economics and Decision Sciences (9%). This demonstrates the interdisciplinary nature of the research, combining engineering, computer and management concepts.

Semantic analysis of keywords (Fig. 4) showed that the most common term is “artificial intelligence” (~215 documents). Also, high frequency are “sustainable development” (114 documents), “energy efficiency” (73), “information management” (63), “machine learning” (56), “smart city” (55), “decision-making” (49), “internet of things” (46), “renewable energy” (34), “smart grid” (29), “big data” (29), “deep learning” (24), “optimization” (23), “digital twin” (10) and “cybersecurity” (9 documents).



Figure 4: Keyword cloud (the larger the font, the more often the term occurs).

Thus, the visualization of keywords confirms that “artificial intelligence” dominates (the largest word in the cloud). Also, very noticeable are “sustainable development”, “energy efficiency”, “information management”, “machine learning”, “smart city” and others – all these concepts form the core of research at the intersection of AI and energy infrastructure. The combinations of keywords indicate that researchers are focused on the topics of sustainable development, energy consumption optimization, the implementation of renewable energy and intelligent energy grid management systems using artificial intelligence.

The results obtained indicate that the integration of artificial intelligence technologies into the management of energy infrastructure development has acquired signs of a sustainable global interdisciplinary direction. This scientific field combines digital, energy and management technologies, forming a new intellectualized model of the functioning of energy systems.

The use of AI technologies makes it possible to increase the efficiency of energy resources, reduce energy consumption, optimize production and technological processes, expand digital management mechanisms and strengthen the resilience of energy infrastructure to external risks, including cyber threats and climate challenges.

In addition, the identified trends confirm the role of artificial intelligence as an important catalyst for the “green” digital transformation of the economy, which corresponds to the logic of implementing the Sustainable Development Goals (SDGs) and forms the basis for the transition to low-carbon energy supply models.

The generalized results of the bibliometric analysis also demonstrate the growing influence of international scientific cooperation, the increasing importance of interdisciplinary research clusters and the gradual institutionalization of a scientific school focused on AI-driven energy infrastructure development management. That is, the research topic moves from the stage of conceptual understanding to the stage of forming mature theoretical and methodological approaches and practical solutions for the energy sector.

The above conclusions create the basis for further critical analysis of the results obtained, which makes it possible to proceed to a discussion of their theoretical and applied implications, as well as to identify the limitations of the research conducted and the directions of future scientific explorations.

5 DISCUSSION, RESEARCH LIMITATIONS AND FUTURE RESEARCH AGENDA

The results of the bibliometric analysis make it possible to rethink not only the current state, but also the internal logic of the evolution of scientific research on the application of artificial intelligence in managing energy infrastructure development. The identified dynamics of publication activity, thematic clusters and international collaboration patterns show that AI-driven energy infrastructure management has moved beyond a purely technological niche and is gradually transforming into a core component of sustainable, digitally governed energy systems.

5.1 Why Do Certain Thematic and Collaboration Clusters Dominate?

The predominance of specific thematic clusters – in particular Intelligent Energy Systems, AI and Sustainable Resource Management and Information Management and Data Analytics – is not accidental. It reflects a combination of at least three groups of drivers.

First, these clusters correspond to areas with the highest data availability and technological readiness. Smart grids, non-intrusive load monitoring, predictive maintenance and energy efficiency optimisation generate large volumes of time-series and sensor data that are particularly suitable for machine learning and deep learning methods. This technological “fit” explains why AI applications concentrate around forecasting, optimisation and anomaly detection in networks rather than, for example, long-term socio-institutional reforms.

Second, the leading clusters are strongly aligned with commercial incentives and investment priorities. Energy companies and technology vendors obtain direct, measurable benefits from reducing network losses, optimising asset management, improving demand forecasting and integrating renewable energy sources. This makes projects in the domains of smart grids, 5G/6G-enabled energy communications and digital twins more attractive for both corporate and public funding than research on, for instance, social perception of AI or ethics-by-design in critical infrastructure.

Third, the structure of scientific collaboration mirrors regulatory and funding architectures. The Indian–Asian and Chinese clusters benefit from large-scale national programmes for energy transition and digitalisation; the Anglo-American and European clusters are shaped by US federal programmes, EU Green Deal, Horizon Europe and Digital Europe initiatives. These frameworks explicitly prioritise AI, cybersecurity and sustainable energy, reinforcing research streams around those policy priorities. By contrast, topics with less clear funding lines – such as distributive justice of AI-driven tariffs or long-term labour market implications in the energy sector – remain underrepresented.

Altogether, the dominance of certain clusters indicates a path-dependent evolution of the field, in which data-rich, commercially profitable and policy-promoted directions systematically receive more scientific attention than equally important, but less easily quantifiable social, ethical and regulatory dimensions.

5.2 Underexplored Dimensions and Knowledge Gaps

The current structure of the field reveals several substantive gaps that limit a holistic understanding of AI-driven energy infrastructure development.

First, social acceptance and public perception of AI in critical energy infrastructure remain insufficiently studied. While sociological and behavioural studies on AI in healthcare or consumer services are growing, the specific perceptions of citizens, local communities and energy consumers regarding AI-based control of grids, dynamic pricing or automated outage management are rarely

addressed in a systematic way. This creates a risk of overlooking resistance, mistrust or low willingness to share data, which may become a binding constraint for large-scale deployment of AI solutions.

Second, there is a lack of integrative research on regulatory and governance frameworks for AI in critical infrastructure. Existing studies usually focus either on technical cybersecurity requirements or on general AI regulation, without fully capturing the interplay between sectoral energy regulation, cybersecurity directives (e.g. NIS2), emerging AI-specific acts and national security strategies. As a result, there is no widely adopted analytical framework that would connect AI capabilities, risk profiles, liability allocation and regulatory design in the energy sector.

Third, economic and financial aspects of AI deployment in energy infrastructure are underrepresented compared to technical studies. Only a limited number of publications provide robust cost–benefit analyses, business models or financing schemes for AI-based retrofitting of networks, creation of digital twins or deployment of advanced decision support systems. Without such analyses it is difficult for regulators and operators to prioritise projects, assess payback periods or design incentives for private investment.

Fourth, the identified geographical asymmetry – with dominance of India, China, the USA and several EU countries, and a weaker representation of Central and Eastern Europe, the Middle East, North Africa and post-conflict economies – indicates a contextual bias of the existing evidence base. The majority of case studies are based on relatively stable, well-capitalised energy systems, whereas the specific challenges of war-affected, highly fragmented or institutionally weak energy sectors remain largely outside the mainstream discourse.

Addressing these gaps requires a deliberate shift from purely technological optimisation towards an integrated perspective that includes governance, economic feasibility, social acceptability and geopolitical vulnerabilities of AI applications in energy infrastructure.

5.3 Conceptual Framework: AI-Enabled Energy Infrastructure Governance

Building on the results of the network and cluster analysis, a conceptual framework of AI-enabled Energy Infrastructure Governance can be proposed to structure the relationships between AI technologies, infrastructure management tasks and target outcomes of energy systems.

The framework consists of three interrelated levels:

Technological layer (AI capabilities and digital enablers).

This layer includes machine learning and deep learning algorithms, reinforcement learning, digital twins, optimisation models, IoT platforms, blockchain-based transaction systems and advanced data analytics. These technologies provide the functional tools for forecasting, optimisation, detection and control.

Infrastructure management layer (decision domains and operational tasks).

At this level, AI is embedded into concrete management functions of energy infrastructure, including:

1) long-term planning and investment prioritisation;
2) operational dispatch and balancing of generation, storage and demand;
3) asset health monitoring, predictive maintenance and outage management;
4) cyber-physical security and anomaly detection;
5) market design, tariff setting and demand response programmes.

Feedback loops connect these tasks with the technological layer: improved data quality and model performance enhances decision-making, while operational decisions generate new data for model refinement.

Outcome layer (system performance and societal goals). The upper level reflects the target indicators that energy infrastructure governance aims to achieve:

1) sustainability and decarbonisation (GHG emissions, share of renewables, circularity of resource use);
2) security and resilience (reliability indices, recovery times after disruptions, cyber-resilience);
3) efficiency and affordability (technical and non-technical losses, operating costs, energy prices);
4) inclusiveness and fairness (equitable access, distributional effects of AI-driven tariffs and services).

Horizontal “governance” and “ethics and regulation” components cut across all three layers. Governance determines how responsibilities for AI deployment are allocated among regulators, operators, technology providers and consumers; the

ethical and regulatory dimension shapes transparency requirements, accountability, data protection and risk-sharing rules.

Graphically, the framework can be presented as a multi-layer diagram linking AI technologies (bottom layer) with management tasks (middle layer) and outcome dimensions (top layer), with bi-directional arrows indicating feedbacks and learning cycles. Such a conceptual model translates the essentially descriptive bibliometric findings into an analytical architecture that can guide empirical studies and policy design.

5.4 Methodological Limitations and Future Research Agenda

The study inevitably faces several methodological limitations typical for bibliometric research. The exclusive use of the Scopus database, without complementary integration of Web of Science, IEEE Xplore or regional databases, may lead to incomplete coverage of relevant works, particularly those published in languages other than English.

Recent publications (2023–2025) have not yet accumulated enough citations to fully reflect their scientific influence, which introduces a time lag into citation-based metrics. Automatic keyword clustering and mapping in VOSviewer may group semantically distinct concepts together or generate doublets, complicating the interpretation of some thematic links.

Finally, bibliometric indicators capture quantitative dimensions of research activity, but they do not directly assess the robustness of empirical methods, the quality of evidence or the practical impact of AI applications on real energy systems.

Recognising these limitations, the findings of this study should be interpreted as a structured "map" of the field rather than a definitive evaluation of specific technologies or projects. At the same time, the results provide a solid foundation for formulating a more focused research agenda that moves beyond description towards explanation and evaluation.

In particular, future research could prioritise the following non-trivial questions:

1) Causal impacts of AI deployment. Under what conditions do AI-based solutions in grid operation, maintenance and planning deliver measurable improvements in energy efficiency, resilience and decarbonisation compared to conventional approaches, once costs and risks are fully accounted for?
2) Regulation–innovation nexus. How do different combinations of energy market design, cybersecurity regulation and emerging AI governance frameworks shape the direction, pace and distribution of AI adoption in critical energy infrastructure?
3) Societal acceptance and distributive effects. How do citizens and energy consumers perceive AI-based decision-making in critical infrastructure, and what are the distributional consequences of AI-driven tariff structures, demand response programmes and automated service provision for vulnerable groups?
4) Economics and financing of AI-enabled infrastructure. What business models and financing mechanisms are most effective for scaling AI solutions in energy infrastructure, especially in countries with constrained fiscal space, high sovereign risk or post-conflict reconstruction needs?
5) Context-sensitive resilience modelling. How can AI-based models incorporate the specific vulnerabilities of energy systems in regions exposed to armed conflict, hybrid threats or extreme climate events, and what indicators best capture AI's contribution to multi-hazard resilience?

Addressing these questions will require combining bibliometric and network analysis with empirical case studies, system dynamics, multi-criteria decision analysis, scenario planning and expert elicitation. Strengthening international cooperation, including with countries in Central and Eastern Europe, the Middle East, North Africa and other transition or post-conflict economies, will be crucial for expanding the empirical basis and ensuring that AI-enabled energy infrastructure governance frameworks are both globally informed and locally relevant.

6 CONCLUSIONS

The study provides an integrated bibliometric and conceptual analysis of the global research landscape on artificial intelligence in energy infrastructure management over 2000–2025. The findings reveal that AI has become a structurally important driver of energy system transformation, shaping the technological, operational and governance foundations of modern energy infrastructures. The exponential growth in publications since 2020 reflects not only technological advances but also the

deepening interdependence between digitalisation, renewable energy integration, cybersecurity and energy resilience.

The analysis demonstrates that the dominance of specific research clusters – such as smart grid optimisation, predictive analytics, digital twins and AI-enabled energy efficiency – is shaped by the interplay of three forces:

1) high data availability and methodological compatibility of these domains with machine learning;
2) strong commercial incentives and investment priorities that favour operational optimisation tasks;
3) regulatory and funding architectures that systematically support digitalisation of energy systems.

At the same time, the study identifies notable knowledge gaps, including limited attention to social acceptance of AI in critical infrastructure, underdeveloped governance and regulatory frameworks, as well as insufficient economic evaluations of AI deployment, especially in countries with constrained resources or post-conflict recovery needs.

Building on the network and thematic mapping results, the research outlines the conceptual foundations of an AI-enabled Energy Infrastructure Governance model, which integrates three analytical layers:

1) technological capabilities (machine learning, digital twins, IoT, optimisation algorithms);
2) infrastructure management tasks (planning, balancing, predictive maintenance, cybersecurity, market design);
3) target outcomes (sustainability, resilience, efficiency, affordability and fairness).

The model emphasises the system-wide feedback loops between data, decision-making and performance indicators, while also incorporating transversal elements of regulation, ethics and accountability. Although presented in an initial conceptual form, the model provides a structured foundation for developing applied tools for evaluation, strategic planning and policy design.

The study contributes to the literature by transforming a predominantly descriptive research field into a more analytical one, offering insights into why certain clusters dominate, what structural gaps persist, and how AI can be embedded into energy infrastructure governance in a way that strengthens sustainability and resilience. These results support policymakers, operators, regulators and researchers in identifying priority directions for responsible AI deployment in the energy sector.

At the same time, the research has several methodological limitations related to reliance on Scopus data, the predominance of English-language publications, and the interpretive nature of cluster aggregation. This implies that the findings should be seen as a comprehensive mapping of global trends rather than an exhaustive evaluation of the effectiveness of AI technologies.

Future research should deepen the analytical implications of the results by focusing on: empirical assessment of the causal impact of AI solutions on energy system performance; integrative regulatory frameworks for AI in critical infrastructure; distributive and societal effects of AI-driven energy management; economic and financial models for large-scale AI deployment; adaptation of AI-based resilience frameworks to fragile, high-risk or post-conflict energy systems.

A separate direction of future work is the full formalisation, operationalisation and empirical testing of the proposed AI-enabled Energy Infrastructure Governance model, which can evolve into a robust analytical and decision-support framework for national and international energy policy.

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Financial Secrecy vs Anti-Money Laundering: Legal and Regulatory Dimensions in a Digitally Driven Global Environment

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Keywords: Security, Economic Openness, Anti-Money Laundering, Corruption, Financial Secrecy, Public Policy, Legal Regulation, Government Regulation, Global Dimension, Interdisciplinary Approach.

Abstract: This research examines the relationships between money laundering risks and financial secrecy levels across different global jurisdictions to formulate proposals for developing effective regulatory policies in the field of financial transparency. To achieve this objective, an interdisciplinary approach was employed, involving a comparative analysis of the Basel AML Index (AMLI) and the Financial Secrecy Index (FSI) for 109 jurisdictions. Visual spatial analysis and multidimensional correspondence analysis were performed using Statistica and RapidMiner statistical packages. A statistically significant relationship was identified between the studied indices ($\chi^2 = 16.73$, $p = 0.04$). Three primary dimensions of interaction were distinguished, explaining 99.9% of the total system inertia. It was established that the categories "low FSI" (31%) and "very high AML" (30%) make the greatest contribution to overall variability. A latent inverse relationship was identified between the highest money laundering risks and the lowest level of financial secrecy, along with associative relationships between medium levels of AMLI and FSI. The unique positioning of jurisdictions with the highest financial transparency was established, which are not associated with any AML categories. It was concluded that the complex nonlinear structure of associations between the studied phenomena requires differentiated approaches to international legal regulation and public administration of financial transparency, taking into account the specific characteristics of national anti-money laundering regimes and legal systems. International organizations can utilize the obtained results to enhance financial risk assessment systems, by national regulators to tailor anti-money laundering legislation to jurisdictional specifics, and by financial institutions to develop more effective compliance control systems and reputational risk management strategies.

1 INTRODUCTION

In the modern interconnected world, the issue of financial transparency has gained critical importance for effective government regulation and public administration. According to estimates by international experts, the volume of money laundering in 2024 ranges from 2.22 to 5.54 trillion US dollars, representing approximately 2–5% of global GDP [1]. This amount passes through the global financial system undetected annually and creates serious challenges for national governments and international organizations in developing effective strategies to combat financial crimes [2], [3].

The paradox of the current situation lies in the fact that despite active efforts by the international community, methods of laundering proceeds from criminal activity are constantly evolving [4]. Criminals use alternative laundering channels in response to the implementation of the Financial Action Task Force (FATF) standards [5] by the

international financial sector. Simultaneously, there is a significant increase in the use of virtual assets in fraud and money laundering schemes [6]. In 2024, illegal activity on blockchain is estimated at approximately 51 billion dollars [7]. In 2022, the United States of America topped the Financial Secrecy Index (FSI) ranking for the first time, surpassing traditional financial centers such as Switzerland and Singapore [8]. This fact changed established perceptions about the geography of financial secrecy and demonstrated that even countries with developed legal regulatory systems can create favorable conditions for asset concealment [9].

Public policy in the field of financial transparency faces complex challenges when it is necessary to balance the requirements of national security, economic competitiveness, and international cooperation. According to Tax Justice Network data, countries worldwide annually lose 492 billion dollars in tax revenue through the use of tax havens by multinational corporations and wealthy individuals [10]. The problem is complicated by the fact that as of 2024, only 33 jurisdictions with significant virtual asset service provider activity are fully or largely compliant with FATF standards, compared to 25 jurisdictions in 2023 [11]. This indicates slow rates of adaptation of national legal systems to the challenges of the digital economy.

International organizations, particularly FATF, continue to improve their approaches to assessing the effectiveness of national anti-money laundering regimes. The Financial Crimes Enforcement Network (FinCEN) regularly informs American financial institutions about updates to the lists of jurisdictions with strategic deficiencies in systems for combating money laundering, terrorism financing, and weapons of mass destruction proliferation [12]. However, the effectiveness of these measures remains a subject of discussion among experts and practitioners.

The results of previous scientific research indicate that regulatory and social factors influence illicit financial flows more than economic factors [13], which confirms the complexity of these relationships. Specifically, the USA received a critical assessment from FATF in 2006 regarding the effectiveness of anti-money laundering efforts, and subsequently topped the FSI [14], which demonstrates the paradoxical relationship between anti-money laundering mechanisms and levels of financial secrecy. Recent analytical studies conducted in [15] revealed an almost 100% correlation between low-risk countries for money laundering and environmental crimes. This suggests the possible existence of hidden structural patterns. Identification of these mechanisms is extremely important for developing scientifically grounded approaches to international policy coordination and forming differentiated public administration strategies in the field of financial security. Currently, a generally recognized effective tool for assessing policy achievements worldwide is the FSI. It provides the ability to determine countries' efforts in developing policies to prevent concealment and laundering of funds by wealthy individuals and criminals [8]. At the same time, one of the most authoritative tools for assessing money laundering risks at the national level remains the Basel AML Index (AMLI) [16].

Contemporary geopolitical transformations and economic challenges caused by the increase in regional military conflicts and sanctions policy have actualized the issue of effective government regulation of financial flows [17]. Countries are forced to reconsider their approaches to balancing economic openness and security, which necessitates conducting a comprehensive analysis of the relationships between different aspects of financial transparency and money laundering risks to form a well-founded state anti-corruption policy. Analysis of these complex relationships can provide an empirical foundation for developing more effective international cooperation strategies and help governments of various countries form differentiated approaches to the legal regulation of financial transparency, as well as develop effective anti-money laundering strategies that consider the specific characteristics of their national financial systems and geopolitical positions.

The purpose of this research is to identify statistical relationships between AMLI and FSI across 109 jurisdictions using correspondence analysis. We hypothesize that these relationships have a complex multidimensional structure characterized by non-linear associations between different risk and secrecy categories, where extreme values of one index do not necessarily correspond to extreme values of the other. Accordingly, the research addresses the following tasks: testing the statistical significance of AMLI-FSI associations, identifying the dimensional structure of their interactions, and determining the spatial positioning patterns of different jurisdiction categories in the correspondence.

2 METHODOLOGY

To investigate the correlation between threats of money laundering and the degree of confidentiality of financial operations in different jurisdictions worldwide, a comparison of AMLI [16] and FSI [8] was conducted for 109 jurisdictions for which values of both indicators are known. AMLI varies from 0 to 10 (where higher values indicate greater risks). It assesses the threat of money laundering and terrorism financing based on the quality of anti-money laundering measures, political and legal risks, as well as financial standards and compliance with international FATF recommendations [12]. FSI is measured from 1 to 141 (higher values correspond to greater secrecy) and considers the level of banking secrecy, corporate transparency, international cooperation in tax matters, and availability of information about beneficial owners, which directly depends on national legislation and its practical implementation. Comparison of these indices allows for identifying gaps in legal regulation and assessing how closely deficiencies in legislative frameworks of financial transparency are related to risks of using financial systems for illegal purposes.

The first stage of our research involved conducting a visual analysis of the spatial distribution of AMLI and FSI for countries included in these rankings. In the second stage, we applied correspondence analysis to identify significant non-obvious relationships between money laundering risk categories and financial secrecy levels in different groups of jurisdictions. This allowed us to reveal statistically significant patterns that are not obvious when visually examining the spatial distributions of the indices.

Correspondence analysis is a multidimensional statistical method designed to investigate relationships between categorical variables through their graphical representation in Euclidean space [18].

The main estimates of the method are:

- Chi-square test determines the statistical significance of the relationship between variables:

$$\chi^2 = \frac{(O-E)^2}{E}, \quad (1)$$

where O – observed frequencies, E – expected frequencies.

- Mass characterizes the relative contribution of each category to the total variance:

$$m_i = \frac{n_i}{n}, \quad (2)$$

where n_i – frequency of the i-th category.

- Quality shows the proportion of point variance explained by the selected principal components:

$$Qali = \cos^2(i_1)\cos^2(i_2). \quad (3)$$

- Inertia reflects the total variance of the system and the measure of deviation from independence:

$$I = \frac{\chi^2}{n}. \quad (4)$$

- Cos² determines the square of the cosine of the angle between the original point and its projection on the principal component, characterizing the quality of point representation on the axis:

$$\cos^2(i_k) = \frac{f_{i_k}^2}{d_i^2}, \quad (5)$$

where f_{i_k} – coordinate of the point on the k-th axis d_i distance from the origin to the point.

Empirical studies were conducted using the Statistica software and RapidMiner artificial intelligence-based data analytics software [19], [20].

3 RESULTS AND DISCUSSION

Figure 1 presents the spatial distribution of AMLI values. The highest money laundering risks are demonstrated by countries of the African continent and some regions of Asia, particularly Congo, Haiti, Myanmar, Mozambique, and Madagascar. Moderate risks are observed in South American countries and part of European states. The lowest risk indicators are found in developed countries of North America and Western Europe, including Finland, Andorra, and Sweden. Australia also belongs to this group. This indicates varying quality of national legal regimes for combating money laundering.

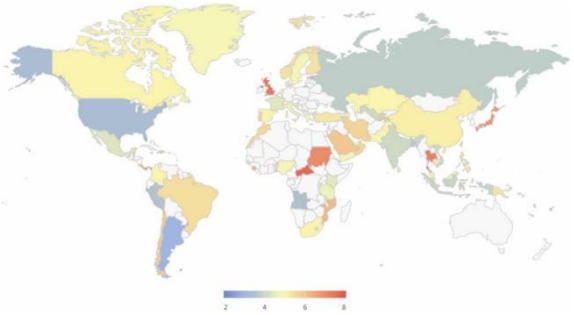


Figure 1: Spatial distribution of Basel AML Index scores.

Figure 2 illustrates the geographical distribution of FSI, where the highest levels of financial secrecy are characteristic of certain offshore jurisdictions, some developed countries such as the USA, Switzerland, the United Kingdom, Japan, Germany,

and Italy, as well as several other international financial centers.

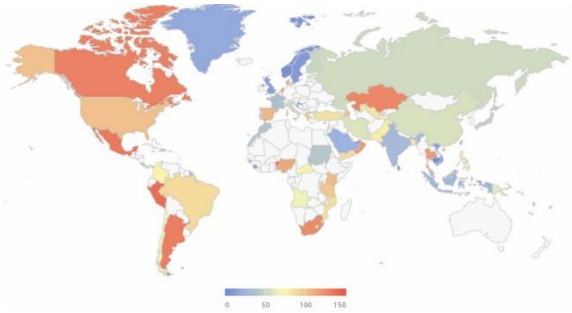


Figure 2: Spatial distribution of Financial Secrecy Index.

This result indicates the complexity of the relationship between different aspects of financial transparency and money laundering risks. This justifies the necessity of applying correspondence analysis, which will enable the identification of non-obvious interesting patterns for understanding the true relationships between these phenomena.

For conducting correspondence analysis, the numerical values of AMLI and FSI were recoded into categorical groups based on the uniform distribution of these indicator values among the analyzed 109 jurisdictions. This categorization allowed for revealing structural relationships between different levels of the studied phenomena.

Table 1 presents the descriptive statistics of the analyzed indices, according to which the recoding was performed.

Table 1: Descriptive Statistics of AMLI and FSI.

Index	Minimum	Maximum	Range
AMLI	2.96	7.59	4.63
FSI	1	138	137

Table 2 describes the algorithm for grouping countries by values of both indices. Each indicator was divided into five categories from “very low” to “very high” values, with clearly defined boundaries for each group.

Table 3 displays the distribution of 109 analyzed jurisdictions across cross-categories of AMLI and FSI.

The largest number of countries is concentrated in the “low AML” category (40 jurisdictions). The fewest countries fell into the “very high AML” category (9 jurisdictions), which indicates an uneven distribution of money laundering risks among the studied countries. This contingency table serves as the basis for conducting correspondence analysis.

Table 2: Grouping of countries by AMLI and FSI values.

Index	Rank	Range
AMLI	very low AML	< 3.9
	low AML	between 3.9 and 4.8
	medium AML	between 4.8 and 5.7
	high AML	between 5.7 and 6.6
	very high AML	>= 6.6
FSI	very low FSI	< 28.5
	low FSI	between 28.5 and 56
	medium FSI	between 56 and 83.5
	high FSI	between 83.5 and 113
	very high FSI	>= 113

Table 3: Summary frequency table for AMLI and FSI.

	AMLI Rank					Total
FSI Rank	very low	low	medi-um	high	very high	
very low	1	11	5	3	1	21
low	2	7	9	3	5	26
medium	3	6	12	2	1	24
high	4	8	6	1	1	20
very high	4	8	4	1	1	18
All gr.	14	40	36	10	9	109

Table 4 presents the results of decomposing the total system inertia into separate dimensions. Its value is 0.15, with Chi-square equal to 29.73 at 16 degrees of freedom and significance level $p = 0.04$. This indicates a statistically significant relationship between the studied indices.

Table 4: Eigenvalues and Inertia for 3 Dimensions for AMLI and FSI.

Dim.	Total Inertia = 0.15, $Chi^2 = 29.73$, df = 16, $p = 0.04$				
	Singular Values	Eigen-Values	Perc. of Inertia	Cumulat. Percent	Chi^2
1	0.28	0.07	47.81	47.81	8.00
2	0.22	0.05	32.84	80.64	5.50
3	0.17	0.02	19.27	99.91	3.22

Three main dimensions of interaction between variables were identified. The first dimension has the highest eigenvalue (0.07) and explains 47.8% of the total system inertia, indicating its dominant role in the structure of relationships. The second dimension with an eigenvalue of 0.05 additionally explains 32.84% of inertia. The third dimension with the smallest eigenvalue of 0.02 contributes 19.27% to the overall explanation. The three dimensions cover 99.9% of inertia, which indicates high quality of the 3-dimensional representation of relationships between money laundering risk categories and financial secrecy levels.

Table 5 presents the results of correspondence analysis for AMLI categories.

Table 5: Column/Row Coordinates (AMLI) and Contributions to Inertia.

Column Name	Mass	Quality	Relat. Inert.	Cos^2 Dim.1	Cos^2 Dim.2	Cos^2 Dim.3
very low	0.13	1.00	0.22	0.39	0.34	0.27
low	0.37	1.00	0.20	0.58	0.41	0.01
medium	0.33	1.00	0.20	0.30	0.52	0.18
high	0.09	1.00	0.08	0.23	0.54	0.22
very high	0.08	1.00	0.30	0.66	0.08	0.27

The largest share (Mass) is represented by countries with "low AML" (0.37), while jurisdictions with "very high AML" are the least represented (0.08). The Quality indicator equals 1.00 for all categories, which indicates high quality of their representation in the three-dimensional correspondence analysis space. Relative Inertia reflects the contribution of each category to the total inertia: the greatest impact is made by the "very high AML" (0.30) and "very low AML" (0.22) categories, indicating their largest deviation from the expected distribution under the assumption of variable independence. The "very high AML" category is best represented by the first dimension (Cos^2 = 0.66), while "high AML" is best represented by the second dimension (Cos^2 = 0.54). This indicates that different levels of money laundering risks have different patterns of interaction with financial secrecy categories.

Table 6 presents the results of correspondence analysis for FSI categories.

Table 6: Row Coordinates (FSI) and Contributions to Inertia.

Row Name	Mass	Quality	Relat. Inert	Cos^2 Dim.1	Cos^2 Dim.2	Cos^2 Dim.3
very low	0.20	1.00	0.23	0.94	0.68	0.23
low	0.24	1.00	0.31	0.85	0.05	0.10
medium	0.22	1.00	0.21	0.08	0.65	0.27
high	0.18	1.00	0.09	0.69	0.18	0.12
very high	0.16	1.00	0.15	0.74	0.01	0.26

By the Mass indicator, the most represented categories are "low FSI" (0.24) and "medium FSI" (0.22). The smallest share is represented by jurisdictions with "very high FSI" (0.16). This indicates a relatively uniform distribution of countries by financial secrecy levels. Quality equals 1.00 for all categories, confirming the high quality of 3-dimensional representation. By the Relative Inertia indicator, the greatest contribution to the total system inertia is made by the "low FSI" (0.31) and "very low FSI" (0.23) categories. This indicates their largest deviation from the expected distribution under the independence hypothesis. Different patterns of financial secrecy category representation were identified. The "very low FSI" category is best described by the first dimension (Cos^2 = 0.94), indicating its clear positioning in the interaction space. The "low FSI" category is also well represented by the first dimension (Cos^2 = 0.85). The "very high FSI" category is distributed between the first (Cos^2 = 0.74) and third (Cos^2 = 0.26) dimensions, indicating a more complex nature of relationships between high levels of financial secrecy and money laundering risk categories.

To improve the interpretation of correspondence analysis results, a three-dimensional visualization of the spatial positioning of AMLI categories (Row Coords.) and FSI categories (Column Coords.) in the coordinates of three main dimensions was constructed (Fig. 3). The diagram clearly shows polarization of categories along the main coordinate axes. The "very high AML" and "very low FSI" categories are located in opposite quadrants of the space, indicating a strong inverse relationship between these extreme categories. Thus, jurisdictions with the highest money laundering risks tend toward the lowest levels of financial secrecy.

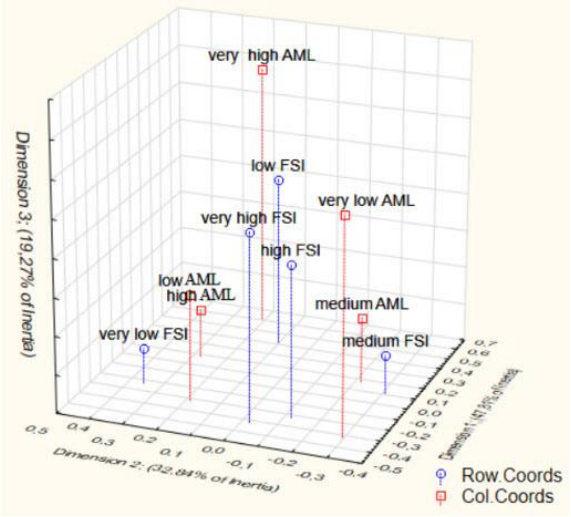


Figure 3: 3D plot of row and column coordinates.

The close positioning of the "medium AML" and "medium FSI" categories in the central zone of the diagram indicates their mutual association. Jurisdictions with moderate levels of financial secrecy have similar moderate levels of money laundering risks. The separate positioning of the "very low FSI" category from all other categories shows its uniqueness in the correspondence space. Jurisdictions with the highest financial transparency occupy a separate position, not associated with any of

the AML categories. The placement of the "low AML" and "very low AML" categories in different sectors of the diagram demonstrates their distinct profiles of relationships with FSI categories. The position of "high FSI" is closer to central categories than to extreme values, which may indicate its intermediate role in the system of relationships between financial secrecy and money laundering risks.

The obtained correspondence analysis results confirm the complex multidimensional nature of relationships between money laundering risks and financial secrecy levels, which cannot be adequately described by simple linear correlations. The statistically significant relationship between the studied indices ($p = 0.04$) and the identified structural associations between their categories indicates the necessity of a comprehensive approach to legal regulation of financial transparency. The absence of a clear correlation between extreme categories of AMLI and FSI suggests the existence of diverse regulatory models, where highly effective anti-money laundering systems can function under different levels of financial secrecy.

The identified associative relationships between medium categories of indices confirm the hypothesis of the existence of a "golden mean" in financial regulation, where balance between transparency and secrecy promotes stability of national financial systems. At the same time, the detection of unique positions of individual categories in the correspondence space demonstrates the diversity of national approaches to ensuring financial security. The obtained estimates indicate the limitations of universal recommendations in the field of anti-money laundering regulation and the necessity of developing differentiated policies that consider specific economic, legal, and institutional characteristics of each jurisdiction when forming effective mechanisms for combating money laundering. The obtained results justify the feasibility of developing composite indicators that combine AMLI and FSI for more accurate risk assessment and the formation of adaptive mechanisms for monitoring financial transactions.

4 CONCLUSIONS

The article examines the relationships between money laundering risks and financial secrecy levels among 109 world jurisdictions. Statistically significant relationships between AMLI and FSI ($\chi^2 = 29.73$, $p = 0.04$) were established. Correspondence analysis revealed three main dimensions of interaction that explain 99.9% of the total system inertia. Key findings reveal that the "low FSI" category makes the greatest contribution to system variability with relative inertia of 0.31 and mass of 0.24, while among AML categories, "very high AML" demonstrates the highest deviation from expected distribution (relative inertia 0.30, mass 0.08). The analysis identified an inverse relationship between "very high AML" and "very low FSI" categories, which occupy opposite positions in the correspondence space, indicating that jurisdictions with the highest money laundering risks tend toward the lowest financial secrecy. Conversely, an associative relationship was found between "medium AML" and "medium FSI" categories positioned in the central zone, suggesting balanced regulatory approaches. Notably, the "very low FSI" category demonstrates unique positioning (Cos^2 Dimension 1 = 0.94), remaining independent from any specific AML risk categories, which indicates that the highest financial transparency operates through mechanisms distinct from traditional anti-money laundering performance.

The scientific novelty consists in: (1) application of multidimensional correspondence analysis to simultaneously examine AMLI and FSI, revealing a three-dimensional structure of relationships; (2) identification of a paradoxical inverse relationship between the highest money laundering risks and lowest financial secrecy levels; (3) empirical demonstration that jurisdictions with maximum transparency form a distinct cluster independent of AML performance categories.

The identified complex nonlinear structure of relationships between AMLI and FSI indicates the necessity of moving away from universal regulatory solutions in favor of differentiated approaches that consider specific characteristics of national legal systems. The existence of balanced jurisdictions with moderate levels of both indicators, as well as the absence of direct associations between extreme categories, points to the possibility of creating effective anti-money laundering mechanisms under different financial confidentiality regimes. This justifies the feasibility of developing a multi-level system of international legal regulation that will allow combining global standards for combating financial crimes with respect for national peculiarities of legal regulation of banking secrecy and corporate transparency.

The obtained results can be used for developing differentiated approaches to international legal regulation of financial transparency, particularly, creating mechanisms for mutual recognition of standards and developing composite indicators for more accurate risk assessment, improving the system for evaluating the effectiveness of national anti-money laundering regimes, and forming targeted

recommendations for different jurisdictions depending on their characteristics.

Promising directions for further research include analyzing the impact of specific legal institutions on the formation of identified interaction patterns, as well as expanding the analysis by including additional indicators of regulatory environment and economic development to build a comprehensive model of financial transparency determinants at the global level.

While this cross-sectional analysis provides insights into structural relationships at a specific point in time, we acknowledge its temporal limitations. Future research will extend the analysis to a multi-year period to examine the stability of identified patterns and reveal potential causal mechanisms and temporal dynamics in the AMLI-FSI relationships.

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AI for Sustainable Hospitality: Guest Perceptions of Green Technologies in Certified Hotels in the Philippines

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Keywords: Artificial Intelligence, Sustainable Hospitality, Green Hotel Certification, Guest Perception.

Abstract: The hospitality industry faces mounting pressure to integrate sustainable practices in response to climate change, resource scarcity, and growing environmental awareness among travellers. Artificial Intelligence (AI) has emerged as a promising tool for enabling green innovations in hotels, particularly those certified under sustainability programs such as ANAHAW, ASEAN Green Hotel Standard, Green Key, and LEED. This study examines guest perceptions of AI-driven green technologies in certified hotels in the Philippines, focusing on awareness, perceived usefulness, and support for eco-friendly initiatives. Using a quantitative, descriptive–correlational approach and Structural Equation Modelling (SEM), data were collected from 350 domestic and international tourists who had recently stayed in certified hotels. Findings reveal that while guests demonstrated moderate to high awareness of AI-enabled green practices, awareness alone did not significantly predict either perceived usefulness or behavioural support. Instead, perceived usefulness emerged as the strongest determinant of support, influencing intentions to revisit, recommend, and pay a premium for environmentally sustainable accommodations. These results highlight the importance of making AI features more visible and directly linked to guest experiences rather than relying solely on awareness. Beyond confirming the predictive strength of TAM, this study contributes originality by extending TAM, in combination with S-O-R and TPB, to the context of AI-enabled sustainability initiatives in certified hotels, offering new insights into guest behaviour in a developing economy. The findings provide practical guidance for hotel managers, certification bodies, and policymakers in aligning technological adoption with sustainability objectives while advancing the hospitality industry's role in sustainable development.

1 INTRODUCTION

The hospitality industry faces growing pressure to adopt sustainable practices in response to climate change, resource scarcity, and consumer concern for the environment. While tourism supports economies, it also contributes to environmental strain through high energy use, water consumption, and waste [1]. With travelers becoming more eco-conscious, hotels are expected to lead sustainability initiatives by adopting green technologies [2], [3]. Artificial Intelligence (AI) plays an important role in this shift, offering applications such as smart thermostats, occupancy-based lighting, predictive maintenance, and real-time monitoring that reduce emissions, improve efficiency, and enhance guest experiences [4]–[7].

Certification programs such as ANAHAW, ASEAN Green Hotel Standard, Green Key and LEED set structured benchmarks for eco-friendly operations in the Philippines [8]–[10]. Certified hotels are expected not only to meet infrastructure standards but also to integrate innovations like AI to complement traditional green practices and meet evolving guest expectations [11]. However, much of the existing literature focuses on managerial or operational perspectives [12], with limited research on guest awareness, perceived usefulness, and support for AI-enabled sustainability, especially in developing economies with resource constraints [13], [14]. Understanding guest perspectives is crucial, as positive perceptions strongly shape behavioral intentions and long-term support for green initiatives [15], [16].

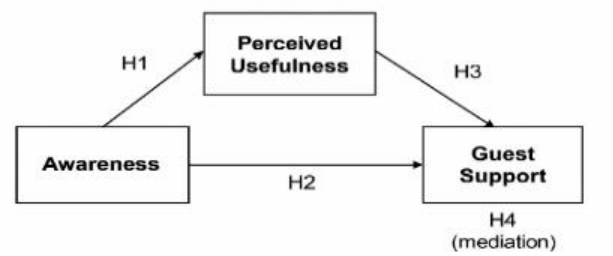


Figure 1: Conceptual framework of the study on harnessing AI for sustainable hospitality: guest perceptions of green technologies in certified hotels in the Philippines.

To address this gap, the study investigates guest perceptions of AI-enabled green technologies in certified sustainable hotels in the Philippines, focusing on awareness, perceived usefulness, and support. Using Structural Equation Modeling (SEM), it analyzes the relationships among these constructs to inform hotel managers, policymakers, and technology providers. The study also contributes to sustainable tourism development while supporting global frameworks such as the United Nations Sustainable Development Goals [10].

2 THEORETICAL FRAMEWORK

This study draws on three complementary theories: the Technology Acceptance Model (TAM), the Stimulus–Organism–Response (S-O-R) model, and the Theory of Planned Behavior (TPB). TAM, developed by Davis [18], explains how perceptions of usefulness drive technology adoption and has been applied in hospitality to AI-based systems such as smart energy management and eco-efficient innovations [5], [18]. The S-O-R model [29] illustrates how external stimuli influence internal states and behaviors; in this study, awareness serves as the stimulus, perceived usefulness the organism, and guest support the response [17], [15]. TPB [26] further highlights how attitudes, norms, and control beliefs shape intentions, with positive views of AI-driven sustainability expected to increase revisit intentions, recommendations, and willingness to pay more [22], [21]. Unlike earlier hospitality research that applied TAM mainly to guest-facing technologies, this study situates it within AI-enabled sustainability practices in certified hotels, an underexplored area in developing economies. By integrating TAM with S-O-R and TPB, the model moves beyond traditional adoption studies to link awareness, usefulness, and pro-environmental intentions, underscoring the study's originality as illustrated in Figure 1.

3 CONCEPTUAL FRAMEWORK

The conceptual framework combines TAM, S-O-R, and TPB to explain how guests respond to AI-enabled sustainability practices in certified hotels. In this model, awareness of AI-driven green technologies is treated as the external stimulus, influencing the internal evaluation of perceived usefulness, which then shapes support behaviors such as revisiting, recommending, and willingness to pay more. Beyond these direct effects, perceived usefulness is expected to act as a mediator between awareness and guest support. To test these relationships, Structural Equation Modeling (SEM) is used to examine both direct and indirect pathways among awareness, perceived usefulness, and guest support.

Hypotheses:

- H1: Guest awareness positively influences the perceived usefulness of AI-driven green technologies.
- H2: Perceived usefulness positively influences guest support for sustainability initiatives in certified hotels.
- H3: Guest awareness positively influences guest support for sustainability initiatives.
- H4: Perceived usefulness mediates the relationship between awareness and support.

4 METHODOLOGY

This study employed a quantitative descriptive–correlational design, utilizing Structural Equation Modeling (SEM) to test both direct and mediating relationships among awareness, perceived usefulness, and guest support. Respondents consisted of domestic and international tourists who had stayed in ANAHAW, Green Key, LEED, or ASEAN Green Hotel Standard-certified hotels within the last 12 months. Participants were selected through purposive sampling, with at least 300 respondents targeted to satisfy SEM requirements [26].

Data were collected using a structured questionnaire adapted from validated scales, covering demographics, awareness, perceived usefulness, and guest support, all measured on a 5-point Likert scale. Reliability and validity were established through Cronbach's alpha, composite reliability, and AVE. To ensure diversity, respondents were recruited through a combination of approaches. On-site surveys were conducted in partnership with certified hotels, where staff invited guests during or after their stay to participate by scanning a QR code. At the same time, online surveys were distributed through booking platforms and travel-related social media groups that catered to domestic and international travelers. While this method broadened the reach of the study, it may also explain why a notable proportion of respondents answered "not sure" to certification-related items, as some guests may have stayed in certified hotels without being aware of the specific certification label. Data analysis included descriptive statistics, SEM modeling with AMOS/SmartPLS, and bootstrapped mediation testing, with model fit indices (CFI, TLI, RMSEA, SRMR) applied following [27]. Ethical standards, including compliance with the Philippine Data Privacy Act of 2012, were strictly observed as shown in Table 1.

Internal reliability was established with Cronbach's alpha values above the .70 threshold for Awareness (α = .893) and Perceived Usefulness (α = .839). Composite reliability (CR) values were also strong: Awareness (CR = .895), Perceived Usefulness (CR = .891), and Guest Support (CR = 1.000). Convergent validity was supported with Average Variance Extracted (AVE) values exceeding .50 for Awareness (AVE = .683) and Perceived Usefulness (AVE = .671). Guest Support, modeled as a higher-order construct, demonstrated acceptable composite reliability (CR = 1.000, AVE = 1.000). Some items (AAGT4, PUADGT4, RI1, and WPM1) exhibited weaker factor loadings. These were retained to preserve the breadth of content validity across awareness, perceived usefulness, and guest support. However, their weaker contributions may have reduced the overall strength of the measurement model. Future studies are encouraged to refine or replace these items to further enhance reliability and construct validity as shown in Table 2.

5 RESULTS AND DISCUSSION

The sample was largely composed of Millennials (50.29%) and Gen X (33.43%), indicating a predominance of working-age adults typically more exposed to sustainability and digital innovations as shown in Table 3. Most respondents were male (67.14%) and earned between ₱20,001–₱40,000 monthly. While 31.14% reported staying in a certified green hotel, nearly half (49.14%) had not, and 19.71% were unsure. A majority (68.00%) were unfamiliar with certification labels such as ANAHAW, Green Key, LEED, and ASEAN Green Hotel, reflecting earlier findings that travelers are eco-conscious but often unaware of specific certification.

Descriptive statistics revealed a high overall awareness of AI-driven green technologies (M = 3.65, SD = 0.77). Guests were most aware of AI applications in waste management systems (M = 4.09, SD = 0.85) and smart sustainability technologies (M = 3.89, SD = 0.99). However, awareness was only moderate regarding the use of AI in monitoring energy and water consumption (M = 2.69, SD = 1.37). This aligns with prior work showing that consumers tend to notice visible and service-related AI applications but are less aware of technical and back-end sustainability functions [5].

As shown in Table 4, respondents reported a high level of perceived usefulness (M = 4.18, SD = 0.57). The highest agreement was with the statement that AI-based sustainability initiatives are innovative and valuable (M = 4.37, SD = 0.60). Respondents also strongly agreed that AI improves operational efficiency (M = 4.23, SD = 0.75). This finding resonates with prior studies which indicate that perceived usefulness is the most critical factor influencing user acceptance of AI and green hotel technologies [28], [29].

Table 5 highlights that guest support was found to be high overall (M = 4.08, SD = 0.43). The strongest support was expressed for booking AI-enabled hotels (M = 4.24, SD = 0.74) and considering AI practices worthwhile investments (M = 4.10, SD = 0.78). This result supports earlier evidence that guests are willing to support sustainability initiatives if they perceive them as valuable and beneficial, even when these involve higher costs [30], [21].

Table 1: Factor loadings and internal reliability and convergent validity.

Construct	Item	Mean	SD	Factor Loading		Cronbach's Alpha	Composite Reliability (CR)	Average Variance Extracted (AVE)
				Initial	Final			
Awareness	AAGT1	3.794	0.912	0.732	0.740	0.893	0.895	0.683
	AAGT2	4.091	0.847	0.710	0.762			
	AAGT3	3.791	1.028	0.884	0.837			
	AAGT4	2.689	1.366	0.225	-			
	AAGT5	3.886	0.993	0.916	0.949			
Perceived Usefulness	PUADGT1	4.077	0.625	0.788	0.783	0.839	0.891	0.671
	PUADGT2	4.231	0.749	0.871	0.877			
	PUADGT3	4.189	0.700	0.784	0.791			
	PUADGT4	4.023	0.941	0.635	-			
	PUADGT5	4.374	0.595	0.794	0.821			
Guest Support	RI1	4.094	0.600	0.461	-	1.000	1.000	1.000
	RI2	4.237	0.739	0.543	-			
	ReI1	3.960	0.679	0.674	-			
	ReI2	4.091	0.773	0.744	1.000			
	WPM1	3.971	0.696	0.509	-			
	WPM2	4.097	0.780	0.603	-			

Table 2: Demographic profile.

Variable	Category	Frequency	Percentage
Age	Gen Z	50	14.29%
	Millennial/ Gen Y	176	50.29%
	Gen X	117	33.43%
	Boomer/Baby Boomer	7	2.00%
Gender	Male	235	67.14%
	Female	113	32.29%
	Prefer not to say	2	0.57%
Monthly Income	Below ₱20,000	8	2.29%
	₱20,001–₱40,000	196	56.00%
	₱40,001–₱60,000	109	31.14%
	₱60,001–₱80,000	37	10.57%
Hotel Stay Frequency	Once	170	48.57%
	2-3 times	132	37.71%
	4-5 times	30	8.57%
	More than 6 times	18	5.14%
Green Hotel Stay	Yes	49	14.00%
	No	2	0.57%
	Not Sure	299	85.43%
Certifications	ANAHW	101	28.86%
	Green Key	130	37.14%
	LEED	44	12.57%
	Not sure	75	21.43%

Table 3: Descriptive statistics of guest awareness of AI-driven Green Technologies.

Item	Statement	M	SD	Interpretation
AAGT1	I am aware that the hotel I stayed in uses AI to conserve energy.	3.79	0.91	High Awareness
AAGT2	I know that AI technologies are used in hotel waste management systems.	4.09	0.85	High Awareness
AAGT3	The hotel provided information about its AI-based sustainability features.	3.79	1.03	High Awareness
AAGT4	I am familiar with the use of AI in monitoring energy and water consumption in hotels.	2.69	1.37	Moderate Awareness
AAGT5	I actively notice smart technologies aimed at promoting sustainability in the hotels I visit.	3.89	0.99	High Awareness
Overall	Guest awareness of AI-driven green technologies (construct level)	3.65	0.77	High Awareness
Note. Responses were measured on a 5-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree).				

Table 4: Descriptive statistics of perceived usefulness of AI-driven green technologies.

Item	Statement	M	SD	Interpretation
PUADGT1	AI technologies in hotels contribute significantly to environmental sustainability.	4.08	0.63	High Usefulness
PUADGT2	I believe AI systems improve the hotel's operational efficiency.	4.23	0.75	Very High Usefulness
PUADGT3	The use of AI in the hotel enhanced my comfort and overall experience.	4.19	0.70	High Usefulness
PUADGT4	AI-driven sustainability features (e.g., smart thermostats) made me feel that the hotel cares for nature.	4.02	0.94	High Usefulness
PUADGT5	I find AI-based sustainability initiatives in hotels to be innovative and valuable.	4.37	0.60	Very High Usefulness
Overall	Perceived usefulness of AI-driven green technologies (construct level)	4.18	0.57	High Usefulness
Note. Responses were measured on a 5-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree).				

Table 5: Descriptive statistics of guest support for AI-driven green initiatives

Item	Statement	M	SD	Interpretation
RI1	I would stay in this hotel again because of its AI-driven green technologies.	4.09	0.60	High Support
RI2	I prefer to book hotels that implement AI-powered sustainability practices.	4.24	0.74	Very High Support
ReI1	I would recommend this hotel to others because of its environmental sustainability practices.	3.96	0.68	High Support
ReI2	I am likely to promote this hotel to my peers due to its use of innovative green technologies.	4.09	0.77	High Support
WPM1	I am willing to pay a higher price to stay in a hotel that uses AI to promote environmental goals.	3.97	0.70	High Support
WPM2	I consider AI-supported green practices a worthwhile investment, even if the room cost is higher.	4.10	0.78	High Support
Overall	Guest support for AI-driven green initiatives (construct level)	4.03	0.62	High Support
Note. Responses were measured on a 5-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree).				

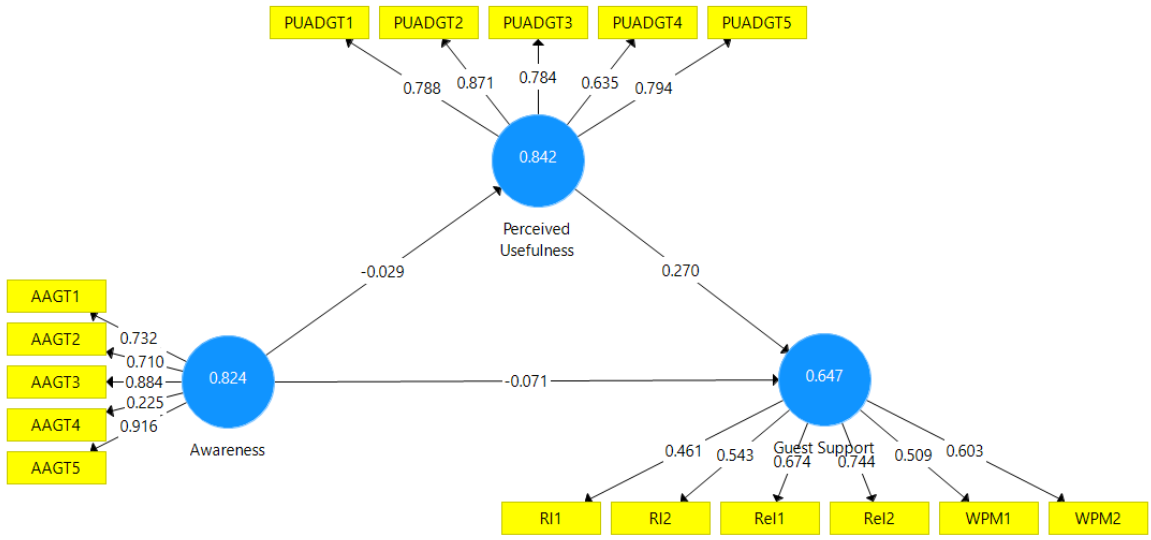


Figure 2: Structural equation modeling results: output loading of factors.

The measurement model was evaluated in terms of factor loadings, reliability, and validity (see Figure 2 and Table 5). For the Awareness construct, four items (AAGT1, AAGT2, AAGT3, AAGT5) were retained with loadings ranging from .740 to .949, while AAGT4 was dropped due to a weak loading (.225). The Perceived Usefulness construct retained four items (PUADGT1, PUADGT2, PUADGT3, PUADGT5) with loadings between .783 and .877; PUADGT4 was removed due to a low loading (.635). All six items of Guest Support (RI1, RI2, ReI1, ReI2, WPM1, WPM2) were retained, with loadings from .461 to .744, though RI1 and WPM1 showed weaker contributions.

Table 6: Fornell-Larcker criterion.

	Aware-ness	Guest Support	Perceived Usefulness
Awareness	0.826		
Guest Support	-0.046	1.000	
Perceived Usefulness	-0.015	0.245	0.819

Table 7: Heterotraiet-Monotrait Ratio (HTMT).

	Aware-ness	Guest Support	Perceived Usefulness
Awareness			
Guest Support	0.029		
Perceived Usefulness	0.046	0.257	

As shown in Table 6, the Fornell–Larcker criterion confirmed discriminant validity, with the square root of each AVE (Awareness = .826; Perceived Usefulness = .819; Guest Support = 1.000) exceeding the inter-construct correlations. Furthermore, the HTMT ratios (Table 7) were well below the conservative threshold of .85 (Awareness–Support = .029; Awareness–Usefulness = .046; Usefulness–Support = .257), providing additional evidence of discriminant validity.

The path coefficients of the structural model are presented in Figure 2. Awareness was not found to significantly predict Perceived Usefulness (β = –.029) nor Guest Support (β = –.071). In contrast, Perceived Usefulness had a positive and meaningful effect on Guest Support (β = .270). These findings suggest that while respondents are generally aware of AI-driven green technologies, this awareness does not directly enhance perceptions of usefulness or support for green initiatives. Instead, Perceived Usefulness serves as the critical driver of Guest Support. The SEM results indicate that awareness alone is insufficient to encourage guest support for AI-driven sustainability initiatives. Guests are more likely to revisit, recommend, or pay more for certified green hotels when they perceive AI technologies as useful in enhancing sustainability, operational efficiency, and their overall hotel experience. Thus, hotels should not only raise awareness but also highlight the practical benefits of AI applications to strengthen guest support [18].

Table 8: Hypothesis testing.

Path Direct Effect	β	t-Value	p-Value	Remarks
H1: Awareness → Guest Support	-0.031	0.651	0.515	Not Significant
H2: Awareness → Perceived Usefulness	0.008	0.182	0.855	Not Significant
H3: Perceived Usefulness → Guest Support	0.249	5.094	0.000	Significant
Note: p < 0.001; Bootstrap resampling with 5,000 subsamples was used to generate estimates.				

Table 8 presents the results of hypothesis testing for the direct effects. The path from awareness to guest support (H1) was not significant (β = –0.031, t = 0.651, p = .515), indicating that awareness of AI-driven green technologies did not directly influence guest support. Similarly, the path from awareness to perceived usefulness (H2) was also nonsignificant (β = 0.008, t = 0.182, p = .855). These results suggest that awareness alone was insufficient to explain variations in either usefulness perceptions or support. In contrast, perceived usefulness demonstrated a significant positive effect on guest support (H3; β = 0.249, t = 5.094, p < .001), confirming that guests who perceived AI-driven green technologies as useful were more likely to support sustainability initiatives. This pattern aligns with prior studies showing that perceived usefulness is often a stronger determinant of behavioral support compared to awareness [18], [32]. Overall, the non-significant paths involving awareness highlight that awareness alone does not meaningfully shape guest perceptions or behaviors, underscoring the need for further analysis of this finding in the discussion.

Table 9: Indirect effects.

Relationship	Indirect Effect			Bootstrapped Confidence Interval		Decision
	β	t-Value	p-Value	95% LL	95% UL	
H4: Awareness → Perceived Usefulness → Guest Support	0.063	0.176	0.860	0.035	0.039	Not Mediated
Note: p < 0.001, LL: Lower level, UL: Upper level						

Table 9 summarizes the mediation analysis. The indirect path from awareness through perceived usefulness to guest support (H4) was not significant (β = 0.063, t = 0.176, p = .860), with confidence intervals crossing zero (LL = 0.035, UL = 0.039). This indicates that perceived usefulness did not mediate the relationship between awareness and guest support. Thus, even though usefulness was a significant direct predictor of support, awareness did not contribute indirectly through usefulness. These findings suggest that increasing awareness alone may not be sufficient to foster guest support unless it simultaneously enhances perceived usefulness.

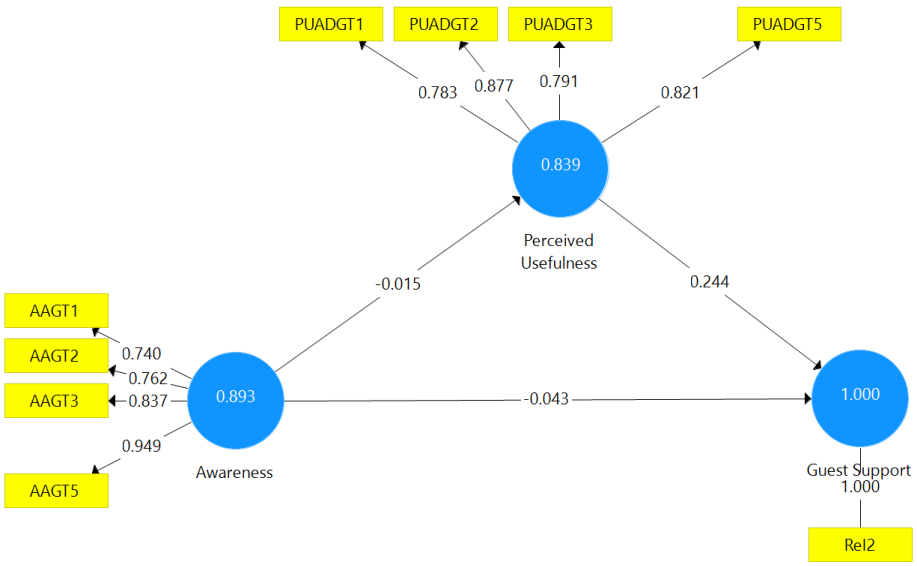


Figure 3: Final SEM model.

Figure 3 illustrates the structural equation model (SEM) of the main hypothesis. The model depicts the direct, indirect, and nonsignificant paths among awareness, perceived usefulness, and guest support. The visual representation reinforces the statistical findings: awareness paths to both guest support and perceived usefulness were weak, whereas perceived usefulness had a stronger direct effect on guest support ($\beta = 0.244$). The model also shows strong outer loadings of perceived usefulness items (ranging from 0.783 to 0.877), indicating reliable measurement of this construct. Awareness items also loaded well, particularly AAGT5 (0.949). However, the weak structural paths confirm that awareness was not a robust driver of usefulness or support.

Table 10: Associated R-square adjusted and R-square.

Construct	R Square	R Square Adjusted
Guest Support	0.062	0.056
Perceived Usefulness	0.000	-0.003

Table 10 reports the coefficient of determination (R^2) values. Guest support had an R^2 of .062 (adjusted $R^2 = .056$), meaning the predictors explained about 6.2% of the variance in guest support. Perceived usefulness had an R^2 of .000 (adjusted $R^2 = –.003$), indicating that awareness explained virtually no variance in usefulness. Following [33] guidelines, these effect sizes are weak, suggesting that the structural model had limited explanatory power. While perceived usefulness still emerged as a meaningful predictor of guest support, the low R^2 values indicate that the model did not fully capture the complexity of guest behavior. Additional factors such as trust in sustainability claims, perceived value of green initiatives, or environmental concern may contribute to a stronger explanatory framework. This limitation is acknowledged, and future studies are encouraged to incorporate these variables to enhance predictive power and provide a more comprehensive understanding of guest support for AI-enabled sustainability practices.

Table 11: Predictive relevance.

Construct	SSO	SSE	Q^2 (=1-SSE/SSO)
Awareness	1400	1400.00	
Guest Support	350	335.57	0.041
Perceived Usefulness	1400	1403.35	-0.002

Table 11 presents the predictive relevance (Q^2) values obtained through blindfolding. Guest support yielded a positive Q^2 value of .041, suggesting small predictive relevance. However, perceived usefulness had a negative Q^2 value (–.002), indicating no predictive relevance. Awareness also produced no predictive relevance. These results reinforce the earlier conclusion that awareness contributed little to predicting guest perceptions or support, while usefulness provided some predictive power for guest support.

Table 12: Model Fit.

Index	Saturated Model	Estimated Model
SRMR	0.062	0.062
d_ULS	0.171	0.171
d_G	0.121	0.121
Chi-Square	239.778	239.778
NFI	0.834	0.834

Table 12 displays model fit indices. The standardized root mean square residual (SRMR) value of .062 fell below the threshold of .08, indicating an acceptable fit [18]. The normed fit index (NFI) was .834, suggesting moderate fit but not reaching the conventional .90 cutoff [34] The chi-square value ($\chi^2 = 239.778$) was statistically significant, which is expected given the sensitivity of chi-square to sample size. Overall, the fit indices suggest that the model was adequate but not strong, consistent with the low explanatory and predictive power of the constructs.

6 CONCLUSIONS

This study examined guest perceptions of AI-driven green technologies in certified hotels in the Philippines and found that while awareness was moderate to high, it did not significantly influence guest support. Instead, perceived usefulness emerged as the strongest driver of revisit intentions, recommendations, and willingness to pay a premium, showing that guests respond more when they see clear benefits such as efficiency, comfort, and innovation. The findings affirm the relevance of TAM in a sustainability context and add originality by integrating TAM with S-O-R and TPB to frame guest behavior in certified hotels within a developing economy. At the same time, the low explanatory power of the model highlights its limitations and signals the need to include other factors – such as trust, perceived value, and environmental concern – in future research. Overall, the study offers balanced insights by recognizing both the strengths and

constraints of the model, while providing practical and policy guidance for advancing sustainable hospitality.

7 RECOMMENDATIONS

The study recommends that hotel operators make AI-enabled sustainability initiatives more visible and directly tied to the guest experience by highlighting certifications, explaining green technologies during check-in, and using in-room displays to show their benefits in real time. Policymakers and certification bodies are likewise encouraged to strengthen standards by not only setting infrastructural requirements but also promoting clear, guest-centered communication of technological advancements to bridge awareness gaps. Finally, future research should consider additional constructs such as trust, perceived value, and environmental concern, and adopt longitudinal and cross-cultural approaches to improve the generalizability of findings.

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Religiosity and Environmental Stewardship: Psychometric Validation of the CRS-5 and Links to Sustainability

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Abstract This study evaluated the psychometric properties and structural validity of the five-item Centrality of Religiosity Scale (CRS-5) in a sample of Filipino university students. It examined implications for ecological attitudes and sustainability engagement. Descriptive statistics and CFA results indicated that CRS-5 is a brief, acceptable measure of centrality of religiosity. Private Practice and Religious Experience showed the strongest relations with the CRS-5 total, highlighting private devotion and experiential spirituality. Regarding the theoretical and empirical links between religiosity and environmental concern, we discuss how dimensions captured by the CRS-5 can support pro-environmental values, collective stewardship, and sustainable behaviors – particularly in societies where religion shapes community norms. The study recommends integrating religious institutions and experiential spirituality into ecological education and sustainability interventions on university campuses. Limitations and directions for research on measurement invariance and the CRS-5's predictive validity for environmental outcomes are noted. Future research should explore longitudinal designs and cross-cultural comparisons to clarify causal pathways linking religiosity and sustainability engagement. Examining how faith-based narratives influence environmental decision-making may further strengthen strategies that harness moral motivation and community solidarity for global ecological responsibility and behavioral change.

1 INTRODUCTION

Religiosity intersects with ecology and sustainability across multiple dimensions, producing both opportunities for environmental stewardship and tensions that complicate unified action [1], [2]. It also influences not only personal worldview and social behavior but also values and practices that relate to environmental stewardship and sustainability [3]. In many communities, including in the Philippines, religious institutions and faith practices shape norms about care for creation, communal resource use, and civic engagement.

The CRS-5's five dimensions (Intellect, Ideology, Public Practice, Private Practice, Religious Experience) map onto pathways by which religion may promote or hinder environmental concern and sustainable action [4]. For example, Ideology can include theological commitments (e.g., stewardship theology) that motivate conservation; Public Practice can mobilize collective action through congregational networks; Private Practice and Religious Experience may cultivate affective connections to the natural world that facilitate pro-environmental values; and Intellect reflects cognitive engagement that may shape environmental knowledge and deliberation.

There have been studies about the Centrality of Religiosity Scale [5] - [9], however this study hopes to evaluate the CRS-5 psychometrically and situates the findings within a sustainability framework to inform ecological education and community-based sustainability programs on university campuses.

An eco-religious approach frames environmental protection and climate change mitigation as integral to religious belief and practice, encouraging adherents to treat the natural world as an object of moral concern rather than solely an anthropocentric resource. This perspective aligns with scholarship arguing that religious institutions and communities can serve as powerful agents of environmental change by mobilizing members, shaping values, and

participating in public education and policy dialogues [1], [4].

Empirical research suggests that religiosity's relationship to environmental attitudes and behaviors is complex and context dependent. Some studies find that religious affiliation and participation are associated with more positive environmental attitudes compared with non-affiliated groups, while other work finds that very high levels of religiosity can coincide with lower environmental concern – especially when doctrinal interpretations prioritize human dominion or when socio-demographic and lifestyle covariates account for observed differences [10]. Moreover, the apparent effect of church membership on ecological values may attenuate once variables such as education, income, and consumption patterns are controlled, indicating that religiosity is one among several interlocking influences on environmental orientation [11], [1].

Case studies from particular cultural contexts illustrate productive pathways through which religion can support sustainability. Research among Muslim consumers in Pakistan reports positive associations between religiosity (both intrinsic and extrinsic) and sustainable behaviors such as energy saving, recycling, and sustainable consumption, although social status concerns can moderate these effects [12]. Similarly, studies among Taiwanese Christians identify church attendance, stewardship beliefs, and environmental-consequence awareness as mechanisms linking faith to protective environmental behaviors and willingness to accept personal sacrifice for environmental goals [13]. These findings point to stewardship theology and environmental education within religious institutions as key levers for promoting both private-sphere behaviors and public activism.

The literature indicates that religiosity interacts with ecology and sustainability in nuanced ways: religious values and institutions may promote bio-centric or eco-centric ethics and lower per-capita ecological footprints in some contexts, yet this relationship is conditional on doctrinal framing, institutional capacity, socio-demographic factors, and the level and type of religiosity among adherents. For research using the CRS-5, these findings suggest treating religiosity both as a multi-dimensional construct (intellect, ideology, public practice, private practice, religious experience) and as a variable whose environmental correlates may vary by cultural context and degree of centrality in an individual's life [4], [11].

2 MANUSCRIPT PREPARATION

Participants and procedure. Participants were recruited using convenience sampling. All participants completed the CRS-5, which comprises one item for each core dimension: Intellect, Ideology, Public Practice, Private Practice, and Religious Experience. Data screening followed standard procedures (missing data, univariate distributional checks, and multivariate normality assessment). Informed consent was obtained from all subjects involved in the study.

3 RESULTS AND DISCUSSION

Descriptive statistics were computed for the five core subscales of the Centrality of Religiosity Scale (CRS-5): Intellect, Ideology, Public Practice, Private Practice, and Religious Experience as presented in Table 1. The means ranged from 3.27 to 4.55, indicating moderate to high religiosity among respondents. Skewness and kurtosis values suggest that the distribution of responses was approximately normal, with slight negative skew observed in Ideology and Private Practice.

Cronbach's alpha for the CRS-5 total scale was 0.78, indicating acceptable internal consistency. While this is slightly lower than the values typically observed for CRS-10 and CRS-15, it reflects the brevity of the five-item model and supports the use of CRS-5 in contexts where time or space constraints exist.

Table 1: Descriptive statistics.

Subscale	Mean	SD	Skewness	Kurtosis
Intellect	3.27	0.9	-0.09	-0.28
Ideology	4.55	0.84	-1.94	3.33
Public Practice	2.88	1.04	0.41	-0.3
Private Practice	4.43	1.05	-1.76	1.89
Religious Experience	3.89	1.05	-0.73	-0.15

Pearson correlation analyses revealed significant and positive relationships among all five CRS-5 subscales and the total religiosity score. The highest correlations were found between Private Practice and CRS-5 Total Score ($r = 0.84$), and Religious Experience and CRS-5 Total Score ($r = 0.85$), followed by Ideology ($r = 0.77$). These results suggest that private forms of religious expression and spiritual experiences are central components of religiosity

among the sample population, as summarized in Table 2.

Table 2: Correlation matrix.

	Intellect	Ideology	Public Practice	Private Practice	Religious Experience	CRS-5 Total
Intellect	1.0	0.117	0.358	0.223	0.203	0.492
Ideology	0.117	1.0	0.377	0.563	0.72	0.766
Public Practice	0.358	0.377	1.0	0.515	0.464	0.708
Private Practice	0.223	0.563	0.515	1.0	0.662	0.839
Religious Experien	c0e.203	0.72	0.464	0.662	1.0	0.847

Mardia's multivariate skewness and kurtosis coefficients were computed to assess normality. The skewness sum was -1.39, and the kurtosis sum was -4.49, indicating acceptable multivariate normality. While not perfect, the data is sufficiently normal to justify CFA procedures using robust estimators.

Independent samples t-tests were conducted to explore potential gender differences in CRS-5 subscale scores. While male participants scored slightly higher across most subscales, none of the differences were statistically significant ($p > .05$). Effect sizes ranged from small to moderate (Cohen's $d = 0.12$ to 0.35), with Private Practice and CRS-5 Total Score showing the largest differences. These findings align with prior research suggesting minimal gender-based differences in religiosity when consideration, as summarized in Table 3.

Table 3: Gender differences.

Subscale	t-value	p-value	Cohen's d
Intellect	-0.604	0.548	-0.154
Ideology	-1.237	0.221	-0.311
Public Practice	-0.483	0.631	-0.122
Private Practice	-1.373	0.175	-0.346
Religious Experience	-1.073	0.287	-0.269
CRS-5 Total Score	-1.357	0.18	-0.341

Although the RMSEA was elevated, the other indices (e.g., CFI, TLI, SRMR, GFI) indicated good to excellent model fit. The inconsistency in RMSEA may be attributed to the small degrees of freedom and model simplicity (Kenny et al., 2015). Standardized factor loadings were all significant ($p < .05$), with the highest loading for Religious Experience (3.186, R- = 0.81) and the lowest for Intellect (1.123, R- = 0.07). This suggests that Religious Experience was the most influential indicator of the latent construct, while Intellect contributed the least. Despite its lower variance, Intellect remains a theoretically important dimension of religiosity, as illustrated in Table 4 and Table 5.

Table 4: CFA model fit indices.

Fit Index	Value	Interpretation
Chi-Square	12.313	Acceptable
CFI	0.975	Excellent
TLI	0.949	Excellent
RMSEA	0.154	Poor
SRMR	0.074	Acceptable
GFI	0.996	Excellent

Table 5: CFA standardized factor loadings.

Subscale	Standardized Loading	R^2
Intellect	1.123	0.066
Ideology	2.927	0.679
Public Practice	2.329	0.43
Private Practice	2.845	0.642
Religious Experience	3.186	0.805

Descriptive statistics revealed moderate to high levels of religiosity, particularly in Ideology and Private Practice. Internal consistency was acceptable (.78), consistent with prior studies of brief religiosity scales. Correlation analysis showed all five subscales were significantly associated with the CRS-5 total score, particularly Religious Experience and Private Practice, highlighting the centrality of affective and devotional aspects of religiosity among Filipino youth.

No statistically significant gender differences were found, although small-to-moderate effect sizes suggest potential trends that future research may further explore. These findings contribute to ongoing discourse on the nuanced relationship between gender and religiosity.

CFA results supported a unidimensional model with most fit indices indicating excellent model fit. Despite a high RMSEA, this may be attributed to model simplicity and limited degrees of freedom. All items loaded significantly onto the latent factor, with Religious Experience showing the highest contribution. Intellect had the lowest explained variance, suggesting this dimension may be better assessed using multiple items in extended versions of the CRS.

This study affirms the validity of the CRS-5 as a brief, practical tool for assessing religiosity, especially where longer instruments are impractical. The results reinforce the importance of experiential

and private dimensions in religiosity and offer insights for culturally sensitive research and intervention in religious contexts.

This study links the five CRS-5 dimensions to processes that plausibly connect religiosity with pro-environmental attitudes and behaviors. The Ideology dimension, which showed a high mean and strong factor loading, appears especially likely to influence collective support for bility when ideological commitments include stewardship, care for creation, or social-justice theology. Where dominant religious teachings foreground compassion and responsibility for others and the natural world, Ideology can reinforce environmental norms and legitimacy for policy interventions that advance sustainable development [1], [4].

Private Practice and Religious Experience – allied affective and experiential aspects of religiosity – displayed very high correlations with total CRS scores and therefore merit particular attention as pathways to nature-connectedness. Affective religious practices (prayer, contemplation) and transcendent experiences can cultivate empathic concern for nonhuman life and feelings of awe, both of which have been linked in prior research to greater ecological concern and conservation behavior. These psychological states can increase willingness to conserve resources and to support conservation policies, suggesting that experiential religion operates as an intrapersonal mechanism for environmental motivation [1], [4].

Public Practice offers an organizational and social mechanism: congregational participation creates social capital and institutional capacity that can be mobilized for community sustainability projects such as tree planting, recycling drives, and disaster risk reduction [3]. Faith communities often provide outreach, environmental education, and trusted networks that lower the costs of collective action and enhance the diffusion of pro-environmental norms [11]. Thus, Public Practice functions both as a platform for behavioral interventions and as a conduit for normative transmission.

The Intellect dimension loaded more weakly in the measurement model, indicating that a single item may insufficiently capture the cognitive and theological reasoning that undergirds environmentally oriented interpretations of faith. Nevertheless, cognitive engagement – scriptural study, theological reflection, and critical reasoning – remains a plausible route to durable attitude change. A richer measurement of Intellect might reveal stronger associations with ecological knowledge, moral reasoning about the environment, and sustained behavioral commitments [4].

Across these dimensions, several mechanisms and contextual moderators clarify when and how religiosity translates into sustainability outcomes. Religious norm transmission via sermons, rituals, and communal teaching can shape personal norms that motivate environmental behavior [11]. Social networks embedded in congregations reduce collective action barriers and enable the scaling of local sustainability efforts. Moral framing that emphasizes stewardship, care for vulnerable populations, or intergenerational responsibility aligns religious language with prevailing sustainability ethics and can enhance public support for environmental policy – especially in highly religious settings where faith-consistent messaging carries credibility [1]. Yet potential tensions persist: doctrinal interpretations that privilege anthropocentric dominion over nature may impede environmental prioritization, making local theological framing a decisive moderator of outcomes [14].

Implications for campus sustainability practice follow directly from these linkages. University sustainability offices should recognize religious communities as strategic partners: partnering with campus chaplaincies and student faith groups can leverage Public Practice to increase participation and legitimacy for sustainability programming. Experiential programming – nature retreats, reflective spiritual practices paired with environmental education – can activate Private Practice and Religious Experience pathways to deepen ecological concern and promote behavior change. Integrating theological reflection into curricular or co-curricular workshops invites Intellect and Ideology engagement, strengthening long-term commitments to sustainable lifestyles. Finally, including brief religiosity measures such as the CRS-5 in program evaluations will allow campus practitioners to assess which religiosity dimensions predict participation, persistence, and behavior change, enabling tailored interventions.

5 LIMITATIONS

Several limitations temper the conclusions that can be drawn. First, the cross-sectional design and CRS-5 measurement preclude causal inference; while dimensions of religiosity are associated with sustainability-relevant outcomes, the directionality of effects cannot be established without longitudinal or experimental data. Second, the CRS-5 subscales use

single items for each dimension; this economical format limits the capacity to represent complex theological positions or to capture the full breadth of cognitive Intellect processes relevant to environmental ethics. Third, cultural specificity constrains generalizability. Findings derived from a Filipino university sample (or any single cultural context) may not extend to other religious traditions, national settings, or age groups because local doctrines, institutional structures, and social norms shape the religiosity–environment relationship [1]. Fourth, unmeasured socio-demographic and lifestyle covariates (e.g., education, income, urban/rural residence, political orientation) may account for part of the observed associations; prior studies have shown that the apparent effect of religious membership on ecological values can attenuate when these factors are controlled [11].

6 CONCLUSIONS

The CRS-5 offers a concise, psychometrically reasonable index of the centrality of religiosity whose dimensions map onto distinct pathways to sustainability. Private Practice and Religious Experience appear especially potent for fostering nature-connectedness and intrapersonal motivations for conservation, whereas Public Practice and Ideology provide social and normative channels for collective action and policy support. Intellect – although less well captured by a single-item indicator – likely represents an underutilized avenue for cultivating durable, theologically grounded commitments to environmental stewardship. By attending to the multidimensional character of religiosity and the contextual factors that shape doctrinal framing, researchers and campus practitioners can more effectively partner with faith communities to promote stewardship and sustainable behavior, while cautiously acknowledging the limits of cross-sectional inference and the need for better measurement and longitudinal evidence. Comparative cross-faith studies might uncover how specific doctrines, rituals, or theological narratives influence sustainable behavior across communities. Integrating psychological and sociological perspectives could also clarify the mediating role of identity, meaning-making, and moral obligation in translating religiosity into ecological action. Moreover, developing more nuanced instruments to assess religious cognition, practice, and experience would strengthen empirical validity and theoretical precision. Longitudinal and intervention-based studies will be essential to trace how religious engagement fosters enduring shifts in environmental attitudes and practices over time.

7 RECOMMENDATIONS FOR FUTURE RESEARCH

To advance understanding of how CRS-5 dimensions relate to sustainable action, future studies should:

1) combine the CRS-5 with validated environmental attitude and behavior scales to establish concurrent and predictive validity;
2) expand the Intellect dimension with multiple items that tap theological reasoning, scriptural interpretation, and environmental moral reasoning;
3) employ longitudinal or intervention designs (for example, randomized trials of faith-based experiential programming) to test causal effects on sustained pro-environmental behavior;
4) examine measurement invariance and conduct multi-group confirmatory factor analyses across religious traditions, age cohorts, and cultural contexts to determine whether the CRS-5 operates equivalently across groups;
5) embed qualitative methods (interviews, focus groups) to reveal the doctrinal narratives, interpretive frames, and institutional dynamics that quantitative scales may miss.

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Ethical Consumerism and Sustainable Apparel Retailing in the Philippines: The Role of Environmental Gatekeepers in Advancing Sustainable Development Goals

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Abstract: The supply chain's retail aspect is still poorly understood despite the increasing prominence of sustainability in the apparel sector. The intricacy of sustainable apparel retailing makes this knowledge gap especially urgent. Theory development, systematic literature reviews, and bibliometric analysis were combined, adhering to the multi-method guidelines of the B-SLR, achieving an integrative examination of the body of dominant literature to address this problem. The suggested hierarchical framework, applicable to diverse consumer segments, delivers a profound understanding of the intricate dynamics underlying sustainable apparel buying patterns. The multi-tiered strategy to recognize consumer preferences and promote eco-friendly apparel combines numerous concepts and components from recognized frameworks, underscoring implementation intentions and buying patterns. It provides conclusive proof supporting the crucial part that consumers' attitudes, morals, awareness, self-reliance, social influences, and emotional ties play in influencing the use of eco-friendly clothing. The generalizability of the results has significant implications for educators, legislators, and retailers who want to advance eco-fashion and environmental preservation.

1 INTRODUCTION

A company's success in the cutthroat apparel sector, where efficient supply chain optimization is critical, depends on balancing the flow of outputs. The ever-evolving fashion trends present apparel retailers with intricate supply chains [1]. In a world with a multitrillion-dollar global economy, the textile and apparel industries are intertwined [2]. This industry provides global supplies by producing everything from fibers to clothing. It is an intricate system that has an impact on the entire world [2]. Known as the worst pollutants in the world, these sectors have millions of workers and contribute 2% of the world's GDP [3]. They are essential to achieving Sustainable Development Goal 12 set by the UN, which highlights the need to change corporate behavior to promote sustainable production and consumption throughout the chain, alongside the EU Commission's Green New Deal initiative [3].

The fashion industry's supply chain involves multiple businesses from product conception to consumer, including growers and retailers, crossing international borders and adhering to trade regulations [1]. According to Statista [4], the combined effects of online shopping and rising demand for clothing would propel retail sales to a 7.6% (CAGR) through 2030.

The global textile industry was severely disrupted by the coronavirus outbreak, which altered supply chains and led to a decline in demand [5]. Due to the evolving customer needs that set a greater focus on environmental responsibility, comfort, and ease of use, the disruption accelerated the industry's shift toward automation and digitalization. As a result, companies have responded by establishing recycling programs, promoting eco-friendly goods, and establishing a variety of partnerships [6].

Due to market conditions, stakeholders in the apparel industry must be adaptable [7]. A strong financial position enables retailers to overcome obstacles and adjust to shifting market conditions

more skillfully [8]. In their role as environmental gatekeepers, they link suppliers and consumers, advocating sustainability and deepening knowledge of social and ecological issues while highlighting the importance of sustainable supply chains [8].

Digital marketing has a huge impact on Filipino consumers' buying choices, especially among younger audiences [9]. Decision-making is accelerated by social media, as users consult their peers' advice and opinions before making purchases [9]. Green ambassadors on social media promote responsible consumption and brand loyalty [10].

Through groups like the decentralized Zero Waste Philippines initiative, which aims to reduce waste, and the Philippine Social Enterprise Network (PhilSEN), which promotes environmentally sustainable practices, the Philippines promotes mindful consumption [11]. By encouraging sustainable waste management in homes and businesses, the government backs these initiatives through R.A. 11367 or the "National Integrated Waste Management Act" of 2019 [11].

Mindful consumption also faces challenges due to limitations in conscious consumerism. A major obstacle is the lack of understanding of consumer behavior regarding sustainability [7]. Key barriers include low awareness, limited resources, and high adoption costs [7]. Consumers prioritize quality, affordability, and convenience over sustainable products [12].

The Philippines' focus on conscious consumerism is a promising development. While sustainable apparel gains attention, the retail aspect remains overlooked. Retailers can reduce emissions and waste through improved operations [13].

This research followed the guidelines of bibliometric analysis and systematic literature reviews to examine sustainable apparel retailing and ethical consumerism, identifying trends, suggesting future directions, and proposing a framework integrating various factors.

2 RESEARCH METHOD

In August 2024, a Scopus search identified 248 papers, with 149 relevant to the apparel industry. A taxonomy from 106 articles categorized themes: sustainable fashion consumption (23 articles), supply chain sustainability (20 articles), consumer psychology (25 articles), cultural influences (18 articles), and marketing strategies (20 articles).

The B-SLR standards [14] employ a holistic approach that integrates systematic literature reviews (SLRs) with bibliometric analysis to create the Biblio-metric-Systematic Literature Reviews (B-SLR). This integrated processes balance quantitative and qualitative methods, addressing the limitations of standalone bibliometric analysis and SLRs, thus enhancing methodological coherence. The structured 10-step process, depicted in Figure 1, facilitated significant literature reviews that improved purpose-method fit [15], [16].

The approach identified gaps in existing frameworks, as presented in Table 1, confirmed relevance, and developed a new framework, enhancing the perception of green apparel purchasing behavior.

The suggested integrated three-tiered framework for sustainable fashion consumer decision-making, illustrated in Figure 2, identified behavioral, sociative, emotive, and cognitive factors influencing Filipino customers, progressing from intention to social influence, purchasing, and culminating in ecological responsibility and self-reliance.

Table 1: Summary of the proposed integrated multi-tiered framework.

Proposed Integrated Framework	Existing Framework	Difference from the Proposed Integrated Framework	Reference
Theory of Planned Behavior (TPB)	Integrated TPB, SCT, and VAB that examine eco-friendly fashion purchasing.	Lacks the ECF and moderating variables.	[17]
Value-Attitude-Behavior (VAB)	Integrated ECF, TPB, and VAB that examine ethical consumerism.	Excludes SCT and SFC.	[18]
Social Cognitive Theory (SCT)	Combined SCT, SFC, and TPB that examine sustainable apparel consumption.	Integrates SCT and TPB but excludes ECF and VAB.	[19]
Sustainable Fashion Consumption (SFC)	Combined VAB, TPB, and SCT that evaluate societal effects.	Comprises SFC and ECF, which are absent from the authors' study.	[20]
Ethical Consumerism Framework (ECF)	Integrated VAB, ECF, and TPB that examine moral consumption.	SCT and SFC are not integrated.	[7]

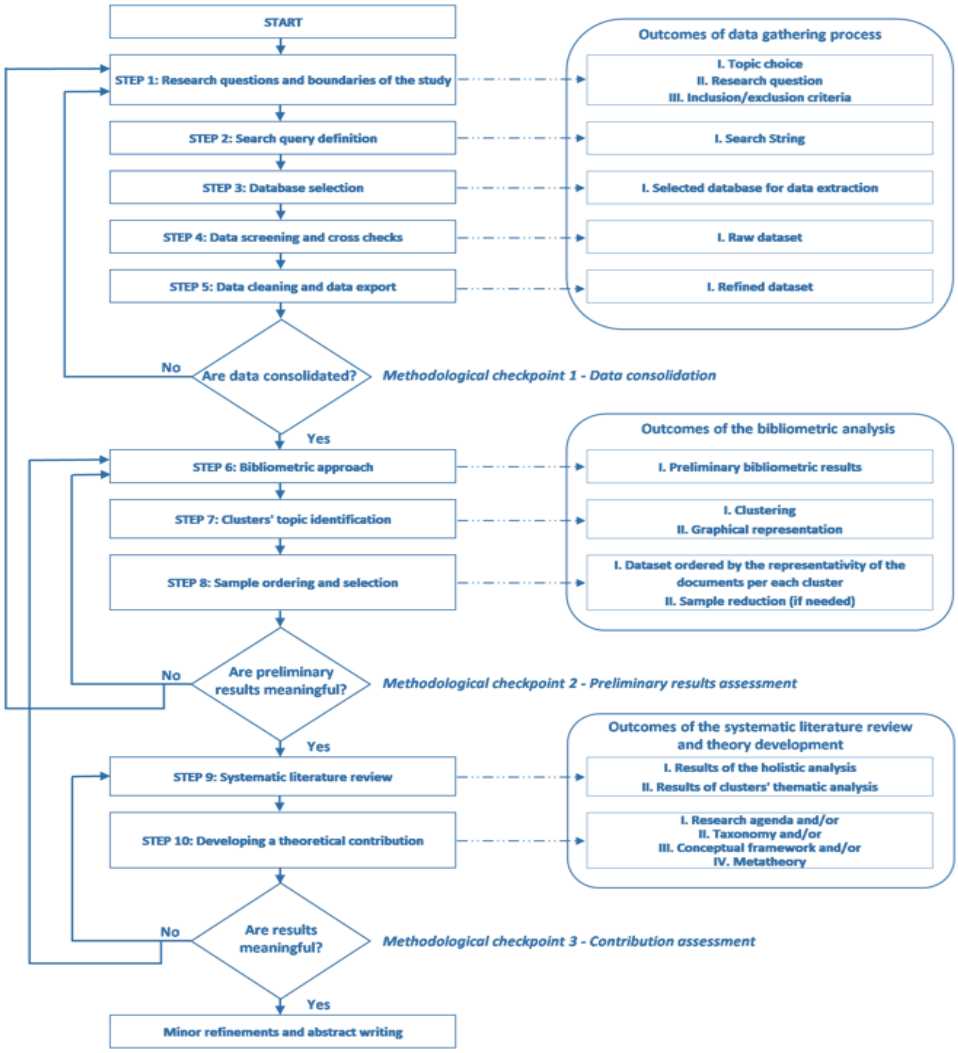


Figure 1: Ten-step bibliometric-systematic literature review workflow.

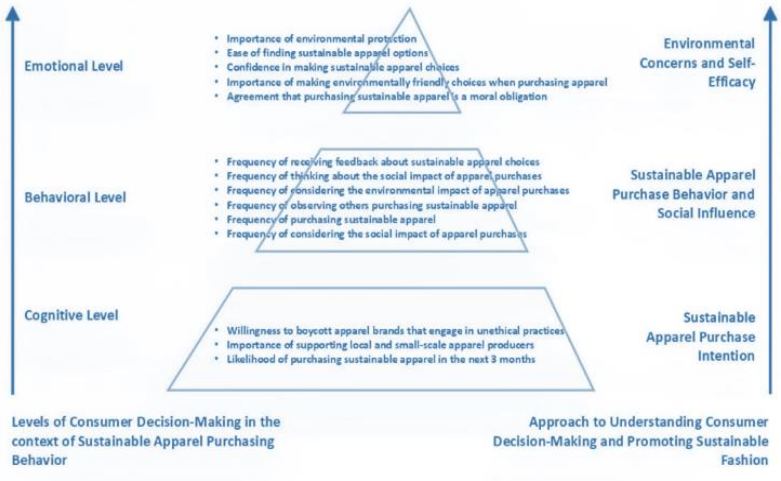


Figure 2: Three-tiered framework for sustainable apparel purchasing behavior.

Table 2: Measurement items, frequency distribution, and constructs.

Constructs/ Items	Rating	Frequency	Median	Mean	Std. Deviation
Ethical Consumerism Theory EC1: How crucial is it to purchase apparel from ethical brands or employers.	3 4 5	320 48 7	3.0	3.165	0.419
EC2: How frequently do you consider how your clothing choices affect society.	1 3 4 5	7 157 204 7	4.0	3.544	0.631
EC3: Would you boycott brands with unethical practices.	1 3 4 5	1,60, 286, 28	4.0	3.907	0.501
EC4: How important is transparency about sustainable practices in apparel retail.	3 4 5	297 71 7	3.0	3.227	0.462
EC5: How important is supporting local/small-scale apparel producers to you.	3 4 5	87 260 28	4.0	3.843	0.532
Theory of Planned Behavior TPB1: Will you buy eco-apparel in the next 3 months.	1 3 4 5	1 86 259 29	4.0	3.840	0.553
TPB2: Do you feel in control of your sustainable clothing choices.	1 5	150 225	5.0	3.400	1.962
TPB3: How important is making eco-friendly apparel choices to you?	3 4 5	37 207 131	4.0	4.251	0.621
TPB4: Are you amenable to paying more for green apparel.	3 4 5	43 51 281	5.0	4.269	1.360
Value-Attitude-Behavior Model VAB1: How important is protecting the environment to you.	3 4 5	73 156 145	4.0	4.193	0.740
VAB2: Is buying sustainable apparel a moral obligation.	3 4 5	29 215 131	4.0	4.272	0.595
VAB3: How frequently do you consider how your clothing purchases will be perceived by others.	1 3 4 5	6 147 178 44	4.0	3.677	0.742
VAB4: How imperative is sustainability when buying clothing,	3 4 5	288 81 36	3.0	3.248	0.468
VAB5: How frequently do you consider how your clothing purchases will affect the environment.	1 3 4 5	6 183 179 7	3.0	3.483	0.620
Social Cognitive Theory SCT1: How often do you see others buying eco-apparel.	1 3 4 5	5 188 175 7	3.0	3.477	0.606
SCT2: Are you confident in making eco-apparel choices.	3 4 5	28 148 199	5.0	4.456	0.631
SCT3: Can you easily find sustainable apparel options.	3 4 5	90 136 149	4.0	4.157	0.784
SCT4: Do you get feedback from others about your sustainable apparel choices.	1 3 4 5	65 144 158 8	3.0	3.117	1.091
Sustainable Fashion Consumption Framework SFC1: How important is it that you cut down on clothing waste	3 4 5	55 209 111	4.0	4.224	1.625
SFC2: Have you ever recycled or restored used clothing.	1 2	208 167	1.0	1.445	0.498
SFC3: How imperative is it for you to buy clothing made from eco materials.	1 2 3 4 5	8 11 43 212 101	4.0	4.032	0.833
Sustainable Apparel Purchase Behavior SAPB1: How often do you buy sustainable clothes.	1 2 3 4 5	8 4 171 181 11	4.0	3.488	0.678
SAPB2: Would you recommend eco-apparel to others.	3 4 5	17 250 108	4.0	4.243	0.525
SAPB3: Are you satisfied with your eco-apparel purchases.	1 3 4 5	1 73 242 59	4.0	3.955	0.612

3 RESULTS

3.1 Knowledge Network Analysis

A bibliometric analysis using Biblioshiny and VOSviewer mapped the evolution of research, presenting visuals such as word cloud, shown in Figure 3, that indicate key themes. The thematic map, illustrated in Figure 4, highlighted knowledge, waste management, and willingness to pay as key themes, with sustainability and ethics becoming increasingly relevant, particularly in 2022.



Figure 3: Word cloud.

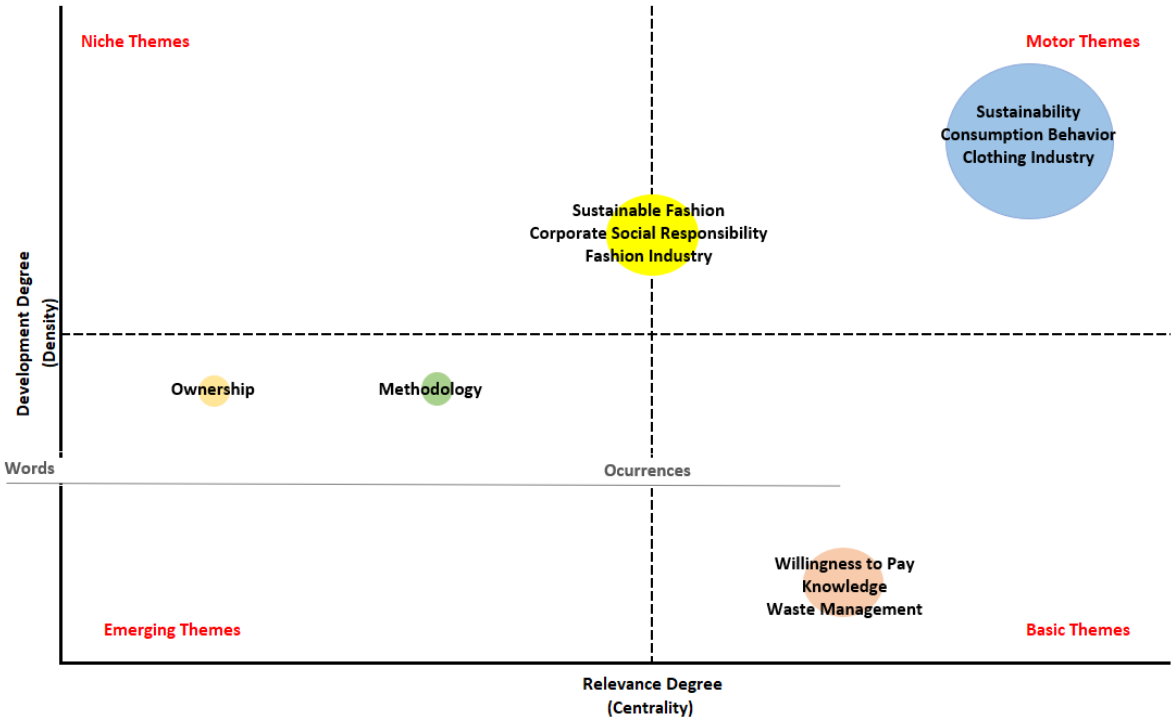


Figure 4: Thematic map.

3.2 Sampling

An online survey via Google Forms revealed six key factors affecting sustainable clothing purchases: demographics, sustainable retailing, ethical consumerism, cultural values, personality traits, and pricing. A quantitative analysis validated findings from 443 respondents, predominantly Gen Z (60.5%). Generational differences affect purchasing priorities, influenced by income and education levels.

3.3 Descriptive Analysis

The variable selection was optimized by analyzing distributions, outliers, and correlations. Table 2 presents the constructs, frequency distributions, and measurement items on sustainable apparel behavior using a Five-point Likert scale.

4 CONCLUSIONS

The sustainability dialogue in fashion frequently overlooks the unique challenges faced by developing countries. This review evaluated sustainable retail practices in the region, identified obstacles, and offered improvement suggestions while emphasizing the necessity for dedicated research on sustainable fashion in underdeveloped markets.

Despite progress, the apparel industry struggles with sustainability and transparency regarding ethical products, impacting consumer attitudes and necessitating the integration of sustainability into retail strategies. Understanding consumer motivations, shaped by social factors and positive sustainability attitudes, is vital amidst rising global environmental concerns.

The study investigated how environmental gatekeepers influence sustainable garment purchasing attitudes among Filipino consumers, advocating for collaboration among regulators, policymakers, and industry stakeholders to foster ethical consumption. Future research should also examine how green supply chain management practices [21] implemented by retailers affect consumer perceptions and purchasing behavior. Education, awareness, and supportive policies are essential to enhance sustainable practices and transform the Philippine apparel market towards ecological responsibility.

The necessity of equitable employment and sustainable economic growth, robust and

environmentally friendly industrialization, and reduced inequities are some of the ways that SDGs 8, 9, 10, and 12 relate to the apparel retailing. Throughout its supply chain, the apparel industry must prioritize moral and fair labor practices, ensuring secure employment settings. Retailers may help by providing access to financial services, supporting small producers, and integrating them into global value chains. A more efficient and responsible sector is encouraged by investments in long-lasting and sustainable infrastructure, which includes both local and international logistics as well as equitable and easily accessible services. Reducing waste and improving resource efficiency requires promoting innovation in circular business processes, sustainable design, and material use. By ensuring fair treatment and opportunities for all supply chain participants, retailers help reduce inequities. Closing social disparities is facilitated by promoting equitable access to reasonably priced, environmentally friendly goods and services and by providing buyers with the information needed to make conscious choices. A fairer and impartial sector is promoted by implementing inclusive strategies that assist local communities and different groups throughout the value chain.

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Islamic Banking Support for Digital Sports Services

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Keywords: Digital Economy, Sports Training, Islamic Finance, Islamic Banking.

Abstract: This study explores the financing of digital sports training services within the broader framework of the rapidly expanding digital economy, with particular emphasis on the potential role of Islamic banks in supporting and sustaining such services. The research sheds light on the specific challenges associated with financing intangible assets, such as mobile applications, online platforms, and other technology-driven tools that form the backbone of modern digital sports services. These assets often lack physical collateral, making their financing more complex, and raising the question of whether Islamic finance can provide Sharia-compliant yet innovative solutions to overcome such barriers. Employing a descriptive-analytical approach, the paper examines the scope of available funding opportunities and evaluates a range of Islamic financial instruments that could be adapted to meet the needs of this emerging sector. Furthermore, it suggests practical mechanisms and strategies to enhance cooperation between Islamic financial institutions and the growing digital sports industry.

1 INTRODUCTION

The world is experiencing a profound digital transformation that permeates all economic sectors, including sports. This technological evolution has catalyzed the proliferation of digital platforms and smart applications for sports training services, fundamentally reshaping service delivery and consumption patterns. While these developments unlock substantial investment opportunities, they simultaneously present financing challenges that necessitate innovative, risk-adaptive financial models attuned to the unique characteristics of digital assets.

In this context, Islamic banking emerges as a viable financing alternative, distinguished by its foundational principles of risk-sharing, equity, transparency, and linkage to real economic activity. These principles offer a robust framework for fostering sustainable growth in digital sports training initiatives. This study examines the convergence of three critical domains – the digital economy, sports training services, and Islamic finance – focusing on opportunities and challenges in leveraging Sharia-compliant mechanisms to support this emerging sector.

2 PROBLEM STATEMENT

Despite the rapid proliferation of digital sports training services and their substantial growth potential, persistent financing barriers impede their optimal development. Unlike traditional ventures, digital economy projects feature intangible assets, distinctive revenue models, and elevated initial risks that misalign with conventional debt-based financing paradigms. Although Islamic banking seeks expansion into emerging sectors, its adaptation to these projects' specialized funding requirements remains nascent.

This study addresses the central research question: What Sharia-compliant mechanisms can effectively bridge the financing gap for digital sports training platforms? Specifically, it evaluates the suitability of partnership-based contracts (*Mudarabah*, *Musharakah*) and sale/lease structures (*Murabahah*, *Ijarah*) for addressing intangible asset financing challenges, while assessing regulatory

frameworks' capacity to support innovative Islamic financial products for this sector.

2.1 Research Questions

How can Islamic banking instruments facilitate sustainable financing for digital sports training services?

2.2 Sub-Questions

To address the study's core objectives, this analysis examines the operational adaptation of Sharia-compliant instruments. The primary sub-questions are:

- How can Islamic financial products - *Murabahah*, *Musharakah*, *Mudarabah*, and *Sukuk* - be optimally structured to accommodate the distinctive financial characteristics of digital sports training platforms?
- What principal challenges and opportunities confront Islamic banking in promoting the growth and sustainability of digital sports training services?

3 HYPOTHESIS

Islamic banking provides effective, sustainable financing for digital sports training services through Sharia-compliant instruments and risk-sharing principles.

Testable Sub-Hypotheses:

- H1. Partnership-based Islamic contracts (*Mudarabah*, *Musharakah*) demonstrate superior suitability over conventional debt models for digital sports projects characterized by intangible assets and elevated initial risks.
- H2. Specialized risk assessment frameworks aligned with Islamic principles, supported by enabling regulatory environments, substantially enhance Islamic institutions' capacity to fund digital sports training initiatives.

4 STUDY OBJECTIVES

This study seeks to:

- Analyze the distinctive financial characteristics of digital sports training service projects.
- Evaluate the suitability of Sharia-compliant Islamic banking instruments for financing these initiatives.
- Identify challenges confronting Islamic banking in this emerging sector and propose mitigation strategies.
- Highlight opportunities for Islamic finance to drive growth and sustainability in digital sports training.
- Offer actionable recommendations for Islamic financial institutions, investors, entrepreneurs, and policymakers.

5 METHODOLOGY AND INSTRUMENTS

5.1 Research Methodology

This study employs a descriptive-analytical approach augmented by empirical validation:

- Descriptive Component. Systematic literature synthesis on the digital economy, sports training services, and Sharia-compliant financial instruments.
- Analytical Component. Examination of variable interrelationships, particularly between Islamic finance mechanisms and digital sports project requirements.
- Empirical Component. Case study analysis of existing financing contracts or expert interviews to substantiate proposed mechanisms.

5.2 Research Instruments

This study utilizes the following instruments to achieve its objectives:

1) Comprehensive Literature Review. Systematic analysis of academic books, peer-reviewed journals, theses, institutional reports, and credible online sources.
2) Content Analysis. Thematic extraction of key concepts, financing models, challenges, and opportunities from collected documents.
3) Case Study Analysis. Examination of actual or illustrative digital sports projects financed through Islamic mechanisms, evaluating implementation challenges and outcomes.
4) Expert Interviews. Semi-structured discussions with Islamic finance specialists and digital sports entrepreneurs to capture practical insights on funding dynamics.

6 THEORETICAL FRAMEWORK AND ANALYSIS

This section presents a comprehensive theoretical framework that integrates literature review findings with analytical discussion, elucidating the compatibility between Islamic banking instruments and the financing requirements of digital sports training services.

6.1 Characteristics of Digital Sports Training Projects

Digital sports training platforms exhibit unique operational characteristics that distinguish them from traditional business models [1]. These ventures are predominantly knowledge-intensive, relying heavily on intangible assets such as proprietary software algorithms [2], mobile applications, digital training content libraries, and user engagement databases. Their revenue streams typically follow subscription-based (SaaS), freemium, or advertising models, which often result in volatile early-stage cash flows and complicate conventional debt-servicing requirements [3]. Moreover, such platforms are exposed to elevated levels of innovation and market risk due to rapid technological obsolescence and uncertain user adoption rates.

6.2 Limitations of Conventional Financing Mechanisms

Traditional debt-based financing proves inadequate for digital sports projects due to several structural mismatches:

- Collateral Deficiency. Banks prioritize tangible assets as security, whereas digital platforms derive value primarily from intellectual property and user networks, which lack conventional collateral value [2].
- Cash Flow Volatility. Fixed repayment obligations exacerbate financial strain during growth phases characterized by negative cash flows and high reinvestment needs. [3].
- Risk Aversion. Conventional lenders exhibit reluctance toward high-uncertainty technology ventures lacking historical performance benchmarks. [4].

6.3 Theoretical Alignment of Islamic Banking Instruments

Islamic finance principles offer a structurally superior alternative through risk-sharing paradigms that align financier and entrepreneur interests:

Risk-Sharing Contracts (Musharakah & Mudarabah). These partnership models eliminate fixed repayment pressures by linking returns to actual project performance. For digital sports startups facing high initial failure probabilities (70-90% within three years), profit-loss sharing reduces entrepreneurial burden while providing financiers equity participation in successful scaling. This mechanism particularly suits subscription-based platforms where revenue stabilization occurs post-user acquisition [5], [6].

Intangible Asset Financing Solutions:

- Istisna' Contracts. Facilitate custom software development and platform engineering, treating digital products as "manufactured goods" eligible for progressive financing [7].
- Ijarah Muntahia Bittamleek. Enables leasing of digital infrastructure benefits (servers, cloud services, software licenses) with ownership transfer, circumventing upfront capital constraints while maintaining Shariah compliance [8].
- Capital Market Instruments. Sukuk issuance leverages stable subscription revenue streams as underlying assets, enabling digital sports firms to access broader ethical investor pools for expansion financing while adhering to asset-backing requirements [4].

6.4 Proposed Analytical Frameworks

The following matrix (Table 1) synthesizes the theoretical applicability of Islamic financing instruments to the components of digital sports training projects. In addition, a comparative risk-based perspective is presented in Table 2.

Table 1: Islamic financing matrix for digital sports training components [7].

Digital Sports Training Project Component	Examples of Components	Proposed Islamic Financing Tool	Mechanism of Suitability
Application / Platform Development	Programming, User Interface Design	Istisna', Diminishing Musharakah	Financing or partnering in the development of digital assets.
Purchase of Technical Equipment	Servers, Cameras, Display Devices	Murabahah, Ijarah Muntahia Bil Tamleek	Financing the purchase of physical assets or leasing them with an option to own.
Production of Training Content	Videos, Written Training Programs	Musharakah, Mudarabah	Partnership in profits/losses resulting from the sale or licensing of content.
Digital Marketing	Advertising Campaigns, Online Promotion	Musharakah, Mudarabah	Financing marketing costs as part of working capital with shared profits.
User Base Expansion	Expansion Costs, Capacity Building	Sukuk (for large projects)	Raising significant capital to finance future growth and expansion.

Table 2: Comparative Risk Framework - Traditional vs. Islamic Financing [9].

Characteristic of Digital Sports Training Project	Impact on Traditional Finance	Impact on Partnership-Based Islamic Finance	Degree of Suitability (Theoretically)
High Reliance on Intangible Assets	Difficulty in providing collateral	Less focus on tangible collateral, more on feasibility	High
Fluctuations in Initial Cash Flows	Increased risk of default	Profit/loss sharing reduces pressure for early repayment	High
High Market and Innovation Risks	Significant hesitation from lenders	Islamic institutions share a portion of the risk	Medium to High
High Scalability Potential	Significant investment opportunities upon success	Potential for high returns for the partnering institution	High
Alignment with Sustainable Development Goals	Not always considered a primary financing factor	Enhances financing attractiveness and aligns with Sharia objectives	High

6.5 Implementation Challenges and Strategic Opportunities

Challenges. Islamic institutions require specialized digital asset valuation expertise, updated Shariah interpretations for blockchain-based contracts, and regulatory frameworks accommodating "Digital Ijarah" and SaaS financing [10].

Strategic Opportunities. Islamic banking can pioneer "FinTech for Good" by capturing ethical investors, portfolio diversification into high-growth sectors, and leadership in SDG-aligned sustainable sports financing [9].

This theoretical framework substantiates the central hypothesis: Islamic banking's risk-sharing architecture provides structural superiority for financing digital sports training services, transcending conventional debt limitations while embedding ethical and sustainability imperatives [1].

7 CONCLUSIONS

This study demonstrates the substantial potential of Islamic banking as a viable and sustainable financing mechanism for digital sports training services within the rapidly expanding digital economy. The findings indicate that the intrinsic characteristics of digital projects – particularly their reliance on intangible assets and volatile early-stage cash flows – are well aligned with the core principles of Islamic finance, including risk-sharing and partnership-based structures.

Through a descriptive-analytical framework supported by theoretical and comparative analysis, the study highlights the relative advantages of Sharia-compliant instruments such as Musharakah, Mudarabah, Ijarah, and Sukuk in addressing the structural limitations of conventional debt-based financing. While challenges remain – particularly in

terms of risk assessment, valuation of intangible assets, and institutional readiness – these constraints are not prohibitive.

On the contrary, the results suggest that Islamic banking institutions are strategically positioned to play a leading role in financing innovation-driven sectors. By leveraging appropriate regulatory support and developing specialized financial tools, they can enhance investment efficiency, attract ethical capital, and contribute to sustainable sectoral growth. Ultimately, this convergence benefits not only entrepreneurs and financial institutions but also broader societal objectives, including improved access to digital health and sports services [1], [8].

8 RECOMMENDATIONS

For Islamic financial institutions:

- Develop specialized risk assessment models for intangible assets and volatile digital cash flows.
- Innovate Sharia-compliant products tailored to digital sports training needs, emphasizing *Musharakah*, *Mudarabah*, and digital *Ijarah*.
- Invest in capacity building for technology and digital business model expertise.

For digital sports entrepreneurs:

- Master Islamic finance principles to optimize funding access.
- Prepare comprehensive feasibility studies highlighting social impact, scalability, and Sharia alignment.

For policymakers:

- Update regulatory frameworks to enable flexible Islamic financing of digital innovation while preserving compliance.
- Foster partnerships between Islamic institutions, sports tech startups, and business accelerators.

Future research directions. Conduct longitudinal case studies of Islamically-financed digital sports projects, evaluating long-term economic and social impacts.

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A Computational Approach to Exchange Rate Policy: Currency Basket Pegging and Its Impact on Iraq's Productive Sector

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Keywords: Exchange Rate Policy, Currency Basket Pegging, Iraqi Economy, Productive Sector, Monetary Policy, Financial Stability.

Abstract: The Iraqi economy faces persistent structural challenges due to its heavy dependence on oil revenues, which account for the majority of public income and limit the development of productive sectors such as industry and agriculture. This study examines the potential of adopting a currency basket peg as an alternative exchange rate policy to enhance monetary stability and support the growth of the real economy. The research analyzes the relationship between exchange rate movements and the performance of productive sectors, highlighting how reliance on a single foreign currency increases vulnerability to external shocks. A conceptual framework is proposed to support the management of a currency basket based on trade patterns and economic indicators. The findings suggest that a diversified exchange rate regime could improve competitiveness, reduce import dependence, and contribute to long-term economic stability. The study concludes that adopting a more flexible and diversified monetary policy may play a significant role in strengthening Iraq's productive capacity and achieving sustainable economic development.

1 INTRODUCTION

The Iraqi economy is going through a critical phase characterized by excessive reliance on oil revenues, a weak production structure, and declining competitiveness in non-oil sectors, particularly industrial and agricultural ones. This reality has led to structural imbalances in the economy, manifested in a trade deficit, high import rates, and a declining contribution of local production to the gross domestic product.

The exchange rate emerges as a key tool that can be used to restore economic balance and stimulate real economic activity. The peg of the Iraqi dinar to the US dollar alone since 2003 has contributed to relative price stability. However, it has made the economy vulnerable to dollar fluctuations, weakened its ability to respond to external shocks, and weakened the competitiveness of domestic products in an open import environment.

Based on this problem, this research seeks to examine the possibility of devaluing the local exchange rate and linking it to a basket of foreign currencies as a strategic option to support the productive sector and raise its efficiency. This approach is expected to increase the competitiveness of local products, stimulate investment in real sectors, and reduce reliance on imports. This will positively impact the overall economy and pave the way for more sustainable and diversified economic development. So the research addresses the relationship between the exchange rate and the efficiency of the productive sector in Iraq, reviews similar international experiences, and proposes monetary policies that can be applied in the economic environment.

Additionally, this study incorporates a computational approach in the sense that it suggests a digital platform of tracking exchange rate variations. The shift to a currency basket would need an algorithmic method of calculating real-time weights on the basis of trade data, so that the monetary policy is periodically operated on the foundation of accurate digital analytics, rather than arbitrary estimation.

2 RESEARCH PROBLEM

The low level of local production in the Iraqi economic environment, and the complete reliance on imports to fill the gap in demand for both agricultural

and industrial consumption. The research also identifies a gap in automated computational frameworks that have the capacity to process real time global market data to support local production.

3 RESEARCH HYPOTHESIS

A decrease in the local exchange rate may contribute to increasing local production, particularly when supported by appropriate economic conditions such as sufficient productive capacity and effective trade policies. The study hypothesizes that an algorithmic approach to currency basket management will increase the precision of Dinar's valuing.

4 IMPORTANCE OF RESEARCH

Achieving relative economic stability by devaluing the exchange rate and pegging it to a basket of currencies aims to reduce the sharp fluctuations associated with pegging the Iraqi dinar solely to the dollar. This enhances monetary stability and reduces the impact of external shocks, especially in a country that relies on oil as its primary source of income.

It is also possible to stimulate local production and reduce imports. As a result, to lower the exchange rate and thus increase the prices of imported goods, making local products more competitive and encouraging the consumption of local production, which enhances the efficiency of the productive sectors, especially industrial and agricultural. Strengthening the productive sector as a result of a balanced policy also contributes to diversifying the structure of the Iraqi economy and reducing dependence on the oil sector as the primary source of GDP. Using a more flexible monetary policy by pegging the dinar to a basket of currencies instead of a single currency gives Iraqi monetary policy greater flexibility to adapt to regional and international variables, especially in light of fluctuations in oil prices and global exchange rates.

The Iraqi economy can also be enabled to withstand external crises by linking the currency to a diverse basket, so that the economy becomes less vulnerable to pressures resulting from changes in the US economy or in the dollar alone, which increases the economy's ability to withstand crises and thus achieves sustainable development goals by stimulating production and employment and increasing local added value. The research also contributes to developing a theoretical and policy framework consistent with the Sustainable Development Goals in Iraq, particularly in poverty reduction, providing decent work, and promoting economic growth.

5 RESEARCH OBJECTIVE

This research aims to analyze the impact of depreciating the local exchange rate and pegging the Iraqi dinar to a basket of foreign currencies on the efficiency of the productive sector in Iraq. This research explores the possibility of adopting a more flexible monetary policy that would stimulate local production, reduce dependence on imports, and achieve sustainable economic stability in light of the challenges facing the rentier Iraqi economy. It also proposes monetary policies that support industrial and agricultural development.

6 THE THEORETICAL FRAMEWORK FOR THE CONCEPT OF EXCHANGE RATE AND PRODUCTIVE SECTORS IN THE IRAQI ECONOMIC ENVIRONMENT

6.1 Exchange Rate

6.1.1 Definition of Exchange Rate

The exchange rate is the ratio between two different currencies, and it determines the value of one country's currency against another. In other words, one currency is converted into another at the rate. For example, if the exchange rate between the US dollar and the euro is $1 = €0.85, this means that $1 US is equal to €0.85. [1]

6.1.2 Types of Exchange Rate System

Global monetary authorities categorize exchange rate regimes based on the degree of flexibility and market intervention into the following systems [2]:

- Floating Exchange Rate. The exchange rate is determined by market mechanisms, meaning that supply and demand for the currency determine its value. A floating exchange rate changes based on economic factors such as inflation, interest rates, and economic policy.

- Fixed exchange rate. The government or central bank sets the exchange rate, pegged to a strong or basket of currencies. For example, pegging the local currency to the US dollar.
- Managed Float. A floating and a fixed exchange rate, where the currency is left to trade freely most of the time, but the central bank may intervene when necessary to stabilize the currency rate.

6.1.3 The Importance of the Exchange Rate

The exchange rate serves as a critical economic instrument that determines the country's international competitiveness through the following key roles [3]:

- International Trade. The exchange rate significantly affects international trade, as a weak currency can make exports cheaper and more competitive while increasing the cost of imports.
- Inflation. The exchange rate can affect the prices of imported goods, thus contributing to inflation in the local economy.
- Foreign investment. The exchange rate influences foreign investment decisions. If the value of the local currency is high, this may attract foreign investment, and vice versa.
- Monetary policies. The exchange rate is a fundamental tool in the monetary policies followed by the central bank to influence the economy.

6.1.4 Factors Affecting the Exchange Rate

The stability and market value of the national currency are influenced by a diverse set of economic and structural factors, including [4]:

- Demand and Supply. The demand for the local currency against foreign currencies is the primary factor in determining the exchange rate.
- Economic benefits. Countries with strong economies and high interest rates tend to attract foreign capital, increasing their currency's demand and value.
- Inflation: Countries with low inflation rates usually have a strong currency.
- Government and central bank policies: Monetary policy decisions and direct interventions by the central bank can affect the exchange rate.
- Future expectations: Expectations about a country's future economic performance also affect the exchange rate.

6.1.5 Economic Theories Related to Exchange Rate Change

The fluctuations in exchange rates are explained by several foundational economic theories that analyze currency value through the following perspectives [5]:

- Power Parity Theory. The Purchasing Power Parity Theory asserts that differences in price levels between countries determine exchange rate changes. In other words, if there are significant differences in commodity prices between two countries, this will lead to adjustments in the exchange rate until the purchasing power between the two currencies is balanced. This theory helps understand how changes in commodity prices can affect a country's economy.
- Continuity Theory (The Mundell-Fleming Model). The Mundell-Fleming model is an economic framework that studies the effects of monetary and fiscal policy on an economy under a flexible exchange rate. According to this model, when countries are open economies with a flexible exchange rate, changes in the latter can significantly impact trade and, consequently, GDP. This model highlights how the interaction between domestic monetary policies and the exchange rate can affect macroeconomic conditions.

6.1.6 The Relationship Between the Exchange Rate and Economic Growth

The exchange rate can affect economic growth in several ways [6]:

- Export incentives. A low exchange rate can encourage the export of goods and services as domestic products become more competitive in global markets.
- Import costs. When the exchange rate rises, import costs can increase, leading to import inflation.
- Foreign investment. Changes in the exchange rate affect foreign capital investments, as investors seek stable exchange rates to reduce risk.

6.2 The Flexibility of the Productive Sectors in the Iraqi Economy

6.2.1 Flexibility of the Production System

It is an economic term that explains the relationship between production inputs on the one hand and production outputs on the other in a country's economy or a specific economy. It is a term with many concepts that express the researcher's viewpoint in a specific specialization. The following are some concepts that explain this term from different viewpoints. Production elasticity represents the percentage change in production (GDP or the production of a single company) divided by the percentage change in inputs or the average output of the production element concerned by the change. The concept of production elasticity can be expressed mathematically in the following formula [7].
Production flexibility

$$EQ = \frac{\partial Q}{\partial X} \cdot \frac{X}{Q}.$$

That is where:

- Q: The outputs represent.
- X: represents the inputs.
- The concept of production flexibility has taken many turns throughout history. A Chinese thinker referred to it 2000 years ago. The concept of production flexibility was used in wars by senior management and their ability to develop production and adapt to the current requirements of those wars. This concept was also used by business organizations during the Industrial Revolution in Europe by many scholars. The first to use this term was the economist Adam Smith in developing production processes in his book (The Wealth of Nations) in 1776, where he considered the positive production characteristic to contribute to improving the status of the facility from changes that occur in the economic environment as a result of disturbances or improvements in the technological situation and other matters that completely or partially affect the production processes and productivity in any institution operating within the economic environment of any country. Some call it the term incremental production flexibility, which expresses the measurement of the speed of production in the number of days it takes a company to achieve a sustainable increase in the manufacturing processes for a specific product in a final form without prior planning [8], as shown:-
- Internal manufacturing capacity determines whether the equipment is operating at full production capacity.
- Regarding resource availability: Are there surpluses or deficits of raw materials
- In terms of labor, is there a labor force capable of production and ready when needed?

6.2.2 Sectoral Interconnectedness and the Development of the Production System

The interconnectedness of the economic sector is a critical issue due to its impact on analyzing and understanding the reality of the volume of current transactions between the various economic sectors and the extent of each sector's dependence on other sectors. It involves studying the quantitative relationships between the economic sectors or the relationships between inputs and outputs, and thus it contributes to defining production and creating added value. The subject of studying sectoral relationships in Oil - producing countries, and specifically the relationship between the oil sector and non-oil sectors, has received special attention from economists and the emergence of many theoretical and applied studies, which adopted the Dutch disease hypothesis, which believes that the increase in revenues Oil will have adverse effects on the development of non- oil sectors, especially in the manufacturing and agricultural sectors. This increase in oil revenues will be accompanied by continuous changes in the elements affecting the external and internal economic balance process. On the external level, this increase will result in a surplus in the balance of payments. This surplus will lead to an increase in the exchange rate of the local currency against foreign currencies, which will in turn lead to a decrease in non-oil local exports, an increase in imports, a decrease in the volume of non-oil production, especially the manufacturing and agricultural sectors, and a deficit in the trade balance of these sectors. In general, the effects can be summarized as follows: The negative impact of the boom on non-oil traded commodity output is twofold: the first is called the resource mobility effect, which is because the rise in oil prices will in turn raise the value of the modern product and the value of the real income of the factors of production employed in this sector, and will lead to the movement of resources and relative advantages towards the oil sector and activities financed by oil revenues (the non-oil traded commodity sector), and away from the non - Oil traded commodity sector (agriculture, industry and manufacturing) [9].

On the other hand, it will lead to a reduction in the marginal product of the factors of production employed in the non-oil commodity sector, and create a surplus in demand for them, making the prices of products of non-traded activities higher than the prices of goods produced in the non-oil commodity sector, especially the prices of agricultural goods, because they are determined in the local market, in addition to the possibility of filling the deficit in their production through imports. The second is the effect of spending. The increase in oil income will increase national income, leading to an increase in aggregate demand and a surplus in demand for the production of various sectors, resulting in another increase in the relative prices of services. This will enable the non-traded goods sector to offer higher wages than the traded goods sector can offer. Oil is a significant source of income; thus, another portion of the resources used in this sector is drawn to the services sector, leading to a further decline in production volume in these sectors. [10]

Therefore, the final result is a decline in the volume of production of the non-oil traded goods sectors, and a decline in their relative importance in the gross domestic product. The danger of this situation lies in the short-term nature of the boom in the oil sector and the long-term adverse structural effects it leaves on the economy. The state of total structural imbalance in the sectoral distribution of activities contributing to the gross domestic product in favor of extractive activities and non-commodity activities ultimately led to the dominance of a single commodity, crude Oil and its products from petroleum and petrochemical derivatives. This matter made the overall economic variables in the Iraqi economy, especially production, operation, investment, consumption, export, import, balance of payments, and government budget, captive to the conditions and fluctuations to which the process of marketing that commodity to international markets is subject. [11]

The Iraqi economy has witnessed fluctuations in the growth rate of the gross domestic product since the beginning of the seventies, during which the non-oil sector could not absorb its undesirable impact on the average per capita income. The contribution of this sector to the gross domestic product is still weak and parallels the population growth rate, which does not add anything to the economic prosperity. Since the Iraqi economy is an oil economy, the fluctuations in global oil prices will be reflected in fluctuations in the economy's growth rates, especially since this source is vulnerable to external shocks, i.e., the national economy's dependence on the fluctuations of the global market. Iraq's oil revenues declined after the global crisis and the decline in oil prices. The contribution of the oil sector's activity to the gross domestic product for the year 2009 declined by 35% compared to the previous year, which was reflected in a decline in the gross domestic product at current prices by 5.10% compared to the previous year, which put Iraq before a difficult challenge. [12]

Iraq has not exploited its oil wealth over the past fifty years to generate sustainable financing to drive development. Hence, there is a need to achieve the goal of diversifying the national economic base and creating diverse incentives for economic growth by focusing on maximizing the added value of Oil and increasing its returns as an entry point for economic diversification. Today, Iraq is required to work on decoupling GDP growth from oil exports, reducing dependence on a single source of income, and moving towards diversification by restructuring the economy at the macro and sectoral levels, in order to reach an economic structure that is compatible with competitive and growth requirements and ensures flexibility in the face of successive changes at the international level through [13]:

- Increasing the role of the private sector and expanding its contribution to the national economy, so that this is reflected in a higher percentage of its contribution to the formation of fixed capital, to the real GDP, and to the non-oil GDP.
- Adopting a financing policy dominated by banking financing instead of relying on the state budget for development financing has transferred widespread financial savings to individuals and institutions. Banks' undertaking of this role in development financing contributes to achieving the goal of development and diversification of sources of income through financing private sector projects in various non-oil economic sectors, which positively impacts the growth and diversification of activities generating non-oil GDP. This trend also contributes to developing the stock market and activating the role of specialized financing institutions in a way that leads to the growth of investments through the impact of this market on developing savings awareness among members of society, pooling national savings and directing them to developing productive assets in the national economy, in addition to establishing holding companies and their role in establishing productive and service projects.
- Export development is essential for any country as it allows it to increase its economic growth

rates and achieve its goals of increasing production capacity, providing job opportunities, and making good use of resources. For example, to achieve industrial development, the government in Saudi Arabia adopted a manufacturing-for-export policy to diversify sources of income and avoid reliance on oil exports, whose prices are subject to fluctuations.

- Supporting small and medium enterprises: Experience has proven that establishing and supporting large-scale enterprises does not necessarily represent the optimal solution to accelerate the development process. Instead, supporting small and medium enterprises, which represent the absolute majority, is the optimal solution to accelerate the development process, given the positive impact of these enterprises on the gross domestic product, savings, investment, consumption, and exports, in addition to their contribution to creating new job opportunities and mitigating inflation.
- Expanding the establishment of joint-stock companies due to their advantages as the most appropriate legal form for creating strong economic entities that can contribute to achieving the goal of development and diversifying sources of income.

6.3 The Current Economic Situation in Iraq

The Iraqi economy heavily depends on oil revenues, constituting more than 90% of the state's revenues. This dependence makes the Iraqi economy vulnerable to global oil price fluctuations, negatively impacting the general budget and economic stability [14].

However, Economic challenges such as unemployment reaching 15%, and poverty affecting about 20% of the population, these challenges increase social tensions and weaken community cohesion. In addition, Iraq suffers from weak infrastructure and deteriorating public services, which hinder economic growth and limit the state's ability to provide decent job opportunities for citizens [15].

Diversifying the economy is essential to reducing dependence on Oil. Sectors such as agriculture and industry can contribute to creating new job opportunities. For example, Iraq can invest in agriculture to achieve food security and reduce import dependence. Improving infrastructure can attract foreign direct investment, which enhances economic growth. Investing in roads, bridges, and energy will improve the business environment and attract investors. Effective economic policies should also focus on supporting small and medium-sized enterprises, a key driver of job creation and economic growth. [16]

7 THE PROPOSED CURRENCY BASKET: A COMPUTATIONAL AND ECONOMIC APPROACH

This section sets the architecture of the proposed currency basket system for Iraq to ensure the integration of economic conceptualization of such a basket system with an advanced computational framework to ensure dynamic stability. The following subsections lay out the theoretical basis, the mechanism for selection, and the automated algorithmic design which must be used for its implementation.

7.1 Economic Theories that Suggest the Need to Link the Local Currency to a Basket of Currencies Instead of a Single Currency

The economic theories that support the idea of linking the local currency to a basket of currencies are divided into several concepts. [17]:

- Economic Stability Theories suggest that pegging a currency to a basket of currencies promotes long-term economic stability. Fluctuations associated with the US dollar, which can be affected by unstable monetary policies or significant market changes, can impact the local economy. The basket provides diversification, reducing the risks associated with any single currency.
- Diversification Theories. Diversification involves using a basket of currencies rather than pegging the local currency to a single currency, such as the dollar. If the dollar's value collapses or deteriorates, the other currencies in the basket can provide a balance, maintaining the relative stability of the local currency.
- Economic integration theories suggest that the global economy has become more integrated, with economies becoming more interdependent. By this logic, pegging a local currency to a basket of currencies aligns with global trade involving a range of currencies, reflecting global economic conditions more accurately.

7.2 Experiences of Countries that have Pegged their Exchange Rates to a Basket of Currencies

The experiment of linking the currency to a basket of currencies was implemented by several countries around the world [18]:

- Hong Kong. Although Hong Kong often relies on the US dollar, its monetary policy includes the flexibility to adjust the currency's exchange rate against a basket of currencies. This protects against US dollar fluctuations.
- Singapore. Singapore is considered a successful model for using a currency basket to stabilize the local currency. The government decided that pegging the currency to a basket of global currencies instead of the US dollar makes the local economy more resilient to global economic changes.
- United Arab Emirates. The UAE follows a fixed exchange rate regime in which the dirham is pegged to the US dollar, unlike basket-based exchange rate arrangements used in some other economies.

7.3 The Impact of Pegging the Local Currency to a Basket of Currencies on The Iraqi Economy

Adopting a diversified currency basket is expected to generate significant structural shifts in the Iraqi economy, primarily through the following impacts [19]:

- Monetary stability. By pegging the Iraqi dinar to a basket of currencies, the adverse effects of fluctuations in the dollar exchange rate can be mitigated, especially since the Iraqi economy is highly dependent on oil, which is typically measured in dollars. This leads to greater stability in the Iraqi dinar exchange rate.
- Improving the trade balance. Iraq relies heavily on oil imports and exports and is sensitive to changes in the dollar exchange rate. Using a currency basket can mitigate the adverse effects of a rising or falling US dollar, helping to improve its trade balance.

7.4 Monetary Policy Challenges in Pegging the Iraqi Dinar to a Basket of Currencies Instead of the Dollar

The transition toward a currency basket introduces several operational and strategic complexities that the Central Bank must manage, specifically regarding the following challenges [20]:

- Political and economic instability. Iraq frequently experiences political and economic instability, making it challenging to implement stable monetary policies. When policies change frequently, strategies such as pegging the currency to a basket of currencies can be challenging to implement effectively.
- Challenges in selecting currencies. Currencies included in the basket must be carefully selected. Some currencies may be subject to high volatility or economic turmoil, which could negatively impact the dinar. The challenge here lies in selecting currencies that accurately reflect the Iraqi economy.
- Managing foreign exchange reserves. Iraq relies primarily on oil revenues to finance its foreign exchange reserves. A currency basket may require complex management of diverse foreign exchange reserves and may increase administrative costs in the event of significant fluctuations in currency values.
- Impact of external factors. External factors, such as global economic crises or changes in the monetary policies of major countries, can affect the effectiveness of pegging the currency to a basket of currencies. The Iraqi economy may be further impacted if an economic crisis occurs in one of the countries whose currency is included in the basket, potentially amplifying the negative economic impact on Iraq.

Therefore, we call on the economic legislator to take his time and seriously study this step in order to make decisions that would preserve the value of the local currency from deterioration, and to mobilize scientific expertise in this field in order to reach steps that would reduce the risks surrounding this process to the minimum possible and benefit from them in raising the efficiency of the local currency in a way that serves the Iraqi economy in the short and medium term, as these terms are linked to the people's livelihood, and to be careful in making decisions and the transparency and clarity of information before starting to work on them, and for society to be informed of these changes that would transfer the Iraqi economy to a better level in the long term.

It is worth noting that the Iraqi government has an Iraqi Economic Council concerned with these matters and is responsible for these decisions, as it includes economic experts and extensive scientific expertise in the Ministry of Higher Education. They should be involved in making new decisions that will increase the benefit and reduce the risks to the minimum

possible at present and bring the Iraqi economy to safety by linking the Iraqi dinar to a basket of foreign currencies and reducing dependence on the US dollar in order to reduce the risks associated with this strong link and avoid the strong effects that the Iraqi economy may enter into as a result of the strong and significant link between the Iraqi economy and the US economy resulting from linking the two currencies together with this strength.

7.5 Proposed Computational Framework for Currency Basket Management

The implementation of the proposed currency basket is anchored in a computational framework as illustrated in Figure 1, which shifts monetary management from manual intervention to being an automated algorithmic system. This framework operates by continually collecting high frequency data from the international financial markets and combining it with Iraq's own specific foreign trade statistics. By using a weight algorithm, the system automatically adjusts the relative significance of each currency that makes up the basket depending on real trade volumes, which also guarantees that the value of the Iraqi dinar is based on realistic economic interdependence rather than static pegging to any single currency [21].

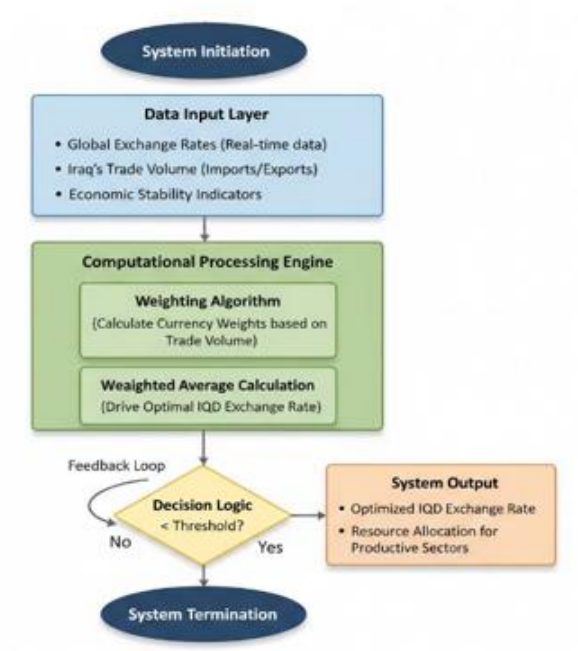


Figure 1: Proposed compitational framework for currency basket weighting Algorithm.

Furthermore, this digital framework is a crucial tool for building resilience of Iraq's productive sectors to global exchange-rates volatility. Through its own integrated feedback loop, the system tracks fluctuations in the economy in real time and adjusts dinar valuation accordingly in order to keep a stable cost environment for local producers who are dependent on importing raw materials. This method of computation not only reduces human error and administrative delays but also allows a data driven transparent mechanism to promote macroeconomic stability and long term industrial growth [22].

8 CONCLUSIONS

This study examined the role of exchange rate policy in shaping the performance of the productive sectors in Iraq, with particular emphasis on the potential adoption of a currency basket peg. The findings indicate that the current reliance on a single currency exposes the Iraqi economy to external vulnerabilities and limits the effectiveness of monetary policy in supporting domestic production.

The analysis demonstrates that a diversified exchange rate regime could enhance economic stability, improve trade balance conditions, and increase the competitiveness of local industries. However, the successful implementation of such a policy requires careful institutional design, strong financial infrastructure, and clear regulatory frameworks.

Overall, transitioning toward a more flexible exchange rate system represents a strategic opportunity for Iraq to reduce its dependence on oil revenues and promote sustainable economic diversification.

9 RECOMMENDATIONS

In order to attain sustainable economic growth and increase the efficiency of the productive sector, the following policy and technical recommendations are proposed in the study:

1) There is a need to change the exchange rate policies currently being followed by the Central Bank of Iraq and implement new policies that will correct the current trends to develop the Iraqi economic environment.
2) The possibility of involving the Iraqi Economic Council in developing detailed plans to achieve results that would achieve economic growth and link the exchange rate to the productive

sectors instead of linking it to the economic growth rate, thus improving the reality of the productive sectors in the Iraqi economic environment.

3) Benefit from the extensive experience of the Ministry of Higher Education and Scientific Research and combine it with experts in the Economic Council to achieve the best in developing economic plans.
4) It is necessary to study the linking of the local currency to a basket of foreign currencies instead of linking the Iraqi dinar to the US dollar, and to study all the positive and negative impacts in the short, medium, and long terms.
5) A comprehensive study of the experiences of countries that have adopted these policies, drawing conclusions and presenting them to decision-makers to reach decisions that will develop the Iraqi economy.
6) Benefit from the accumulated expertise in scientific research at Iraqi universities and connect this expertise with decision-makers, without the need for intermediaries, in aspects related to developing policies that would improve the Iraqi economy.
7) the creation of an AI-based digital platform to automate the calculation of the weight of the proposed currency basket according to trade dynamics.

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Digital Payment Systems in Iraq: Current Status and Development Challenges

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Keywords: Electronic Payment, Financial Environment, Financial Inclusion, Financial Development.

Abstract: The global landscape is evolving towards a more sophisticated digital framework that fosters artificial intelligence and delivers superior services to customers both domestically and internationally, promoting competition and accelerating the enhancement of digital infrastructure around the world. This research aims to assess the development of electronic payment services in Iraq and investigate whether they have made significant progress that aligns with the Central Bank of Iraq's strategy for financial inclusion and stability, which is a crucial step towards encouraging banks and other financial institutions to cooperate and collaborate in enhancing financial access and investing capital in local production sectors. The study posits that the advancement of electronic payment services is adequate to improve the efficiency of Iraqi banks in utilizing funds to bolster the local economy. The findings indicated that electronic payment services in Iraq were limited during the research timeframe. The research recommended that the Central Bank of Iraq regularly assess digital banking performance, focusing on the implementation of digital cybersecurity measures and protection standards, the ongoing enhancement of digital functionalities and services, and their incorporation into the annual evaluations of these banks. It also urged other economic institutions to embrace advanced digital transformation across all commercial, production, and other operations.

1 INTRODUCTION

The shift towards electronic payment methods is a reflection of advancements in banking and the growing dependence on banking services for executing commercial transactions and various business operations. Iraq faces a considerable delay in the acceptance of electronic payment systems by both merchants and consumers. This situation has created a significant hurdle for the Central Bank of Iraq in establishing an electronic payment framework and integrating it into ongoing transactions. Payments primarily conducted in cash dominate the financial settlements involving credit and debit cards for sales and purchases. This dominance has put considerable strain on banks, which have localized the salaries of public sector employees to maximize the availability of ATMs, allowing for immediate cash withdrawals.

Problem Statement. The adoption of advanced banking practices for electronic payments encounters a psychological obstacle among consumers when carrying out financial transactions. Additionally, numerous retailers are hesitant to utilize bank cards for settling debts, which has restricted the proliferation of electronic payment solutions throughout the Iraqi economy.

Importance of the Research. Digital payment solutions enable the easy, efficient, and secure execution of financial exchanges between parties involved in a transaction. This removes the necessity of handling significant sums of cash and alleviates issues related to varying denominations due to heightened usage (rapid circulation of money). Each of these transactions takes place within encrypted and secure bank accounts in the financial system, enhancing the efficiency of banking operations and boosting its functions throughout the economy.

Research Hypothesis. The research assumes that the development of electronic payment services will enhance the efficiency of Iraqi banks in deploying funds to serve the local economy.

Research Objective. The research aims to monitor the development of electronic payment services in Iraq and determine whether they have achieved tangible progress that supports the Central Bank of Iraq's approach to financial inclusion and stability. This strategy represents an important step toward mobilizing banks and other financial institutions to collaborate and cooperate with each other to increase financial access and capital investment in local production sectors.

Research Methodology. Official data issued by the Central Bank of Iraq through its annual publications was used for the period (2017-2023), and the indicators of electronic payment services were analyzed based on the data and trends of the values of the indicators.

2 LITERATURE REVIEW

The electronic payments sector is undergoing a radical shift towards instant payments and central bank digital currencies (CBDCs). The Global Findex 2025 report highlights That Digital savings growth is expected to reach 40% by 2024, marking the fastest increase in a decade, in developing economies. Smart coverage: 84% of adults in low- and middle-income countries own mobile phones, including 3 billion smartphones, which has boosted access to integrated payments. Transformed financial behavior: 79% of adults globally now have accounts, with mobile money playing a pivotal role in changing traditional financial behavior [1].

The IMF's Financial Access Survey (FAS 2025) revealed the following: A transaction boom: Digital transactions (via mobile and internet) in emerging economies increased from 55 transactions per adult in 2017 to 251 transactions in 2024. International remittances: The share of digital remittance flows increased from 13% in 2019 to 46% by 2024, significantly reducing costs. Central bank digital currencies (CBDCs): The IMF's 2025 report indicates that 19 countries in the Middle East and Central Asia are currently exploring the issuance of digital currencies to enhance payment efficiency and financial inclusion [2].

Regarding Fast Payments and Inclusion (FASTT) initiatives, the State of Instant Payments Systems 2025 report highlighted the FASTT project: the World Bank supports countries in establishing fast payment systems to boost trade and create jobs. Instant payments: In Africa alone, instant payments reached $2 trillion, driving growth and digital inclusion. Artificial intelligence integration: By 2025, 80% of fintech companies would have begun implementing AI to improve customer experience (83%) and reduce costs (75%). [3].

Accordingly, the advancement of electronic payment methods creates an attractive financial environment for the rapid development of the advanced financial instruments industry for settling electronic financial transactions worldwide. In this regard, the most important steps taken by the world can be summarized as follows [4]:

1) Shift from "Disruption" to "Cooperation": The fintech industry has moved from disrupting traditional systems to "collaborative transformation" and integration with existing financial infrastructure.
2) Centralization of "Instant Payments". 24/7 payment systems are becoming the new standard for boosting productivity and financial inclusion, particularly in Latin America and Africa.
3) Challenging Technical Standards. The World Development Report 2025 asserts that "international standards" are the underlying infrastructure of modern economies, and that aligning domestic markets with these standards is essential for export growth and technology flow.
4) Macroeconomic Impact. Central bank digital currencies (CBDCs) can strengthen monetary policy transmission channels and reduce "dollarization" or "crypto-ization" if properly designed. 5. The digital divide: Despite progress, a third of the world's population will still be offline in 2024, with the cost of broadband remaining a major obstacle in low-income countries (consuming 29% of monthly income).

3 THEORETICAL FRAMEWORKS FOR ELECTRONIC PAYMENT METHODS

3.1 Concept of Electronic Payment Methods

The concept of electronic payment refers to a form of electronic money transaction that involves settling debts, conducting purchases, or other forms of payment. It includes all payment methods that leverage modern technology to meet financial obligations, such as electronic funds transfers, e-

checks, electronic bills of exchange, card payments, and digital cash transactions [5].

It is also described as a collection of banking instruments and procedures that encompass the electronic trading and transfer of funds, serving as a mediator between the payer and the recipient [6]. Furthermore, it is explained as (a collection of banking practices, guidelines, instruments, and procedures that enable the trading of funds and offer payment services to individuals and businesses through participating banks and financial institutions in accordance with electronic systems) [7]. Additionally, it is characterized as (a cohesive set of tools and methods that streamline financial transactions among institutions, as they aim to enhance the economy's welfare by lowering capital costs, reducing financial risks, and strengthening financial intermediation) [8].

The most important factors that led to the introduction of electronic payment methods are the following:

1) The gradual decline in the effectiveness of traditional payment methods over time.
2) The widespread use of the internet in banking activities.
3) The global trend towards e-commerce.
4) The digital trend due to the COVID-19 pandemic.

3.2 Characteristics of Electronic Payment Methods

The most important characteristics of electronic payment methods are the following [9], [10].

Ease of use of electronic payment methods without complications and without routine and administrative procedures.

1) Access to financial services: Electronic payment methods can provide access to financial services for groups that do not have bank accounts or do not have sufficient access to traditional financial services.
2) They are characterized by security, reliability, ease, and fluidity.
3) Organized management by the entity providing the electronic payment service.
4) Speed in completing transactions, transparency in financial transfers, and savings in many fees charged for financial transactions.
5) They have an international character, meaning they confer an international character on payment methods and are globally accepted.

3.3 The Importance of Electronic Payment Methods

The importance of electronic payment methods is evident in the following: [11], [12]:

1) Their importance to the financial sector, as they aim to reduce financial risks and increase credibility, speed, and security. Secure and efficient payment systems also represent an important mechanism that supports the functions of financial markets and the financial system. Electronic payment systems enable financial transactions between banks to be completed easily and quickly, reducing the percentage of cash in circulation and ensuring the availability of complete information on cash management. [13].
2) The Importance of Electronic Payment Methods in Fiscal Policy: Electronic payment methods can enhance fiscal policy through the government's use of electronic payment methods, which leads to increased public revenues through the easy and rapid collection of taxes and fees electronically, and reduces tax evasion through the availability of accurate records of financial transactions. The government can also support social support programs by providing secure and fast payment methods for beneficiaries. Increasing government revenues reduces government debt, especially in developing countries [14].
3) The importance of electronic payment methods for individuals, as they provide them with speed and security in completing their cash transactions without difficulty, and facilitate the completion and settlement of financial accounts for all companies and their local and international branches with ease and accuracy.
4) The importance of electronic payment methods in recording accounts related to exports and imports within the scope of electronic systems, especially in rentier economies with increasing oil revenues and consumer imports [15].

4 THE DEVELOPMENT OF ELECTRONIC PAYMENT METHODS IN IRAQ

4.1 Number of POC Devices

The proliferation of point-of-sale (POS) devices has been a recurring phenomenon. Looking at the

timeline of this proliferation, we find fluctuations between decline and rapid growth, reaching record levels. However, a gap still exists between the current number of devices and market expectations.

As part of the Central Bank of Iraq's efforts to promote financial inclusion and modernize the banking system, the state has adopted an ambitious strategy to move towards electronic payments. These policies have been directly reflected in the payments infrastructure, as statistical data have shown rapid growth in the spread of digital payment tools and the expansion of their use in commercial activities.

The number of POS devices in 2017 was 13.8 devices per 100,000 people (Fig. 1). It increased to 17.3 devices per 100,000 people in 2018, and then gradually increased until it reached 62.5 devices per 100,000 people in 2020. In 2022, it reached its highest level, at 75.7 devices per 100,000 people.

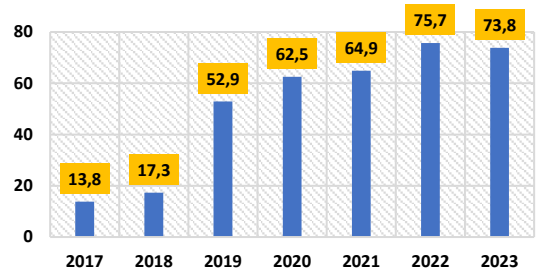


Figure 1: Number of POC devices in Iraq for (2017-2023) (per 100,000 people). Source: CBI, Financial Stability Report, various years.

A parallel analysis of POS deployment shows that in 2017, the number stood at 2.5 devices per 100,000 people (Fig. 2). This number continued to increase until it reached 10.1 devices per 100,000 people in 2019. Thereafter, the culture of electronic payment became more widespread in the Iraqi economy, reaching 35.8 devices per 100,000 people in 2021. In 2023, it reached its highest level, at 71 devices per 100,000 people.

Despite the development in the use of POS devices, their use remains modest and insufficient, not commensurate with the volume of transactions being processed through these devices on an ongoing basis. It appears that electronic payment habits, despite a slow start, have subsequently accelerated following the Central Bank of Iraq's clear adoption of an electronic payment strategy, which obligates banks to use and disseminate them within the community. The spread of these devices is closely linked to markets, shops, and malls that have begun to accept cashless settlements using credit cards, Visa cards, and other methods.

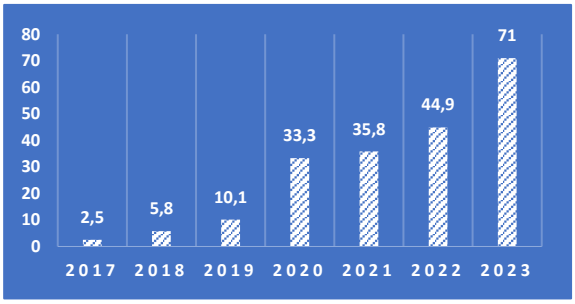


Figure 2: Number of POS devices in Iraq for (2017-2023) (per 100,000 people). Source: CBI, Financial Stability Report, various years.

It is worth noting that the Central Bank of Iraq established the National Company for Electronic Payment Systems in Iraq in 2023 [16]. The Central Bank explained that the company represents a qualitative development in the country's financial infrastructure. The new company will be responsible for developing, operating, and managing the national electronic payment and clearing systems with high efficiency, and will add new elements to serve the electronic payment environment.

4.2 Number of ATMs

Automated teller machines (ATMs) are the cornerstone of access to banking services and a vital indicator of the level of financial inclusion in society. Despite the upward trend in their deployment in recent years, the gap between numerical growth and geographical expansion continues to influence individuals' attitudes towards digital transformation, as the following data demonstrates.

The number of ATMs in 2017 was 1.8 machines per 100,000 people (Fig. 3). This trend continued to increase over the research period, reaching 5.9 machines per 100,000 people in 2020, and then 12.4 machines per 100,000 people in 2023. Despite the increasing trend of ATMs, their prevalence remains limited across public facilities, government institutions, and private institutions. Perhaps the limited prevalence of ATMs is driving a decline in the use of electronic payment cards among the population, as there is still a widespread tendency among society to use cash to settle financial obligations.

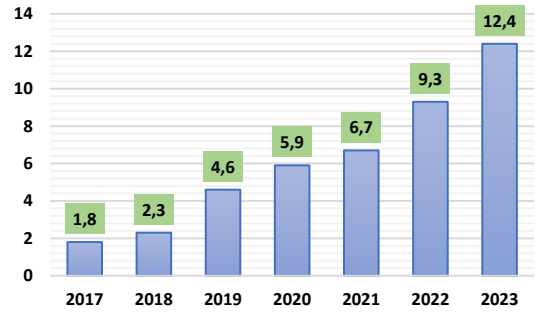


Figure 3: Number of ATM devices in Iraq for (2017-2023) (per 100,000 people). Source: CBI, Financial Stability Report, various years.

4.3 Cash Transfer from Mobile

The mobile payment market in Iraq has witnessed fierce competition among licensed companies, with varying levels of market share and performance depending on public trust and the services offered. Statistical indicators for money transfer rates reveal that three main companies lead the scene (Zain Cash, Asia Hawala, and Nass Wallet), with significant shifts in their market shares observed, as illustrated in the following table.

Asia Hawala, Zain Cash, and Nas Wallet were the companies with the highest mobile cash transfer rates (Table 1). Zain Cash topped the list, with transfer rates ranging from a maximum of 98.8% in 2023 to a minimum of 26.1% in 2017. Asia Hawala followed, with transfer rates ranging from a maximum of 73.9% in 2017 to a minimum of 0.3% in 2023. Nas Wallet followed, with only a minimum of 0.3% for the period 2021-2023.

Table 1: Cash transfer from mobile payment companies in Iraq for (2017-2023) (%) [16].

Years	Asia Hawala	Zain Cash	Nas Wallet
2017	73.9	26.1	0
2018	53.6	46.4	0
2019	48.8	51.2	0
2020	32.6	67.4	0
2021	18	78.7	3.2
2022	8.3	84.5	7.3
2023	0.3	98.8	0.8

It is worth noting that the Central Bank of Iraq has imposed a ban on dealing with a number of electronic payment companies and financial platforms, such as PayPal, Perfect Money, Web Money, and Binance. Due to the Central Bank of Iraq's failure to comply with applicable financial regulations and laws, local alternatives such as Zain Cash, Asia Pay, Switch, Q-Card, Amwal, Fast Pay, Nas Wallet, and others have been provided. However, cash transfers in Iraq remain weak, and their role was very limited during the research period.

4.4 Bank Accounts, Electronic Cards, And Electronic Wallets

Bank accounts and electronic cards play a significant role in enhancing electronic payment methods by providing easy and secure financial means for managing money. Electronic cards enable easy and secure cash withdrawals and payments. Bank accounts also enable the opening of deposit accounts, making financial transfers, and receiving wages, salaries, bonuses, and other benefits securely and efficiently.

The annual growth rate of bank accounts in 2018 was 86.4% (Fig. 4). It rose to 101.6% in 2020, after which it began to decline due to the repercussions of the health crisis and quarantine measures. The annual growth rate of bank accounts in 2023 reached 51.1%, following the recovery of financial transactions in general. The annual growth rate of electronic cards in 2018 reached 19.3%, and declined significantly in 2020, reaching 11.8%, and in 2022 it reached its lowest level at 8.7%, which is evidence of the weak use of electronic cards in daily settlements of consumer and financial transactions.

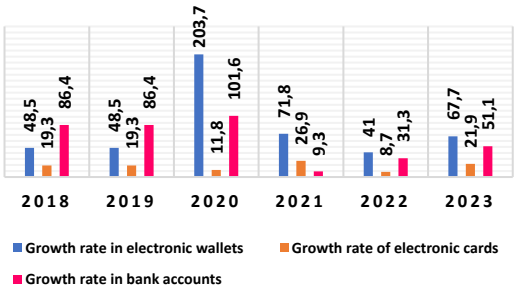


Figure 4: Growth rates of bank accounts, electronic cards, and electronic wallets in Iraq for (2018-2023) (%). Source: CBI, Financial Stability Report, various years.

The annual growth rate of electronic wallets in 2018 reached 48.5%, and reached its highest level in 2020, reaching 203.7%. This indicates the emergence of a desire among users to build their electronic cash wallets to benefit from them in cash transfer operations and completing their daily financial transactions, until it reached 67.7% in 2023. This indicates the importance of creating electronic cash wallets during the research period among users in

order to complete their commercial and daily transactions, which means that individuals prefer electronic wallets over other electronic payment methods in the Iraqi economy.

It is evident from the previous discussion that all electronic payment methods are infrequently utilized by individuals in their everyday transactions. The acceptance of electronic payments encounters several obstacles, primarily the population's hesitance to adopt them due to their relatively recent introduction. In addition, many people find the costs associated with electronic transactions to be prohibitive, which deters usage. Furthermore, the lack of strong financial infrastructure and the limited effort from banks in promoting and fostering the culture of electronic payments have contributed to a decrease in the adoption of these methods, coupled with a general unfamiliarity with how they function. Additionally, users are hesitant to embrace these methods due to concerns over fraud, scams, and the possibility of their electronic accounts being hacked, which could result in financial losses without adequate legal recourse or oversight for such cybercrimes. This situation has prompted the government to implement cutting-edge cybersecurity measures to combat these threats. The creation of the National Company for Electronic Payment Systems also significantly contributes to resolving these issues.

5 CONCLUSIONS

The small number of POC devices during the research period indicates a limited spread of their use across the Iraqi economy. Although some growth was observed after 2020, the number of point-of-sale devices remains insufficient and does not correspond to the population increase, which has exceeded 40 million people. Similarly, the number of ATMs is still low, and their availability across public and private sectors remains modest and below expectations. This limited infrastructure constrains the effectiveness of banking operations and does not adequately support the expansion of financial inclusion across all Iraqi governorates.

Cash transfers through local companies also require greater diversification, as the market has been largely dominated by a few providers, particularly Zain Cash and Asia Hawala, throughout the research period. In addition, the role of major international money transfer companies remains weak, limiting competition and innovation in the sector.

Furthermore, the ranking of electronic banking activities based on annual growth shows that electronic wallets occupy the leading position, followed by bank accounts, while electronic cards rank last. This pattern suggests that electronic payment practices in Iraq continue to face structural challenges, particularly those related to financial infrastructure and customer trust, which affect the widespread adoption of these technologies in everyday financial transactions.

6 RECOMMENDATIONS

To enhance the effectiveness of electronic payment systems in Iraq, several policy and operational measures should be considered. First, it is essential to expand the deployment of POS devices across all commercial sectors by encouraging their adoption among institutions, companies, retailers, and service providers. This should be complemented by increasing the number of ATMs in public facilities, government institutions, commercial areas, as well as cultural and tourist locations, in order to improve access to banking services and support financial inclusion.

Second, efforts should be made to strengthen the competitiveness of the money transfer sector by supporting the development of local service providers while simultaneously allowing reputable international companies to operate within the regulatory framework established by the Central Bank of Iraq. Establishing partnerships and joint operational agreements between local and international providers could further enhance service quality, technological capabilities, and market efficiency.

Finally, promoting financial literacy and increasing public awareness of electronic payment systems are critical for their widespread adoption. This can be achieved through targeted advertising, educational programs, and promotional campaigns aimed at building trust in digital financial services and encouraging individuals to transition from cash-based transactions to secure and efficient electronic payment methods.

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Digital Economy Impact on E-Commerce and Consumer Behaviour in Iraq

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Keywords: Digital Economy, E-Commerce, Consumer Behavior, Iraq, Online Transactions.

Abstract: The swift evolution of the digital economy has rewritten global business models, especially in e-commerce, altering consumer buying behaviors. In Iraq, internet expansion, mobile technology, and digital payment solutions have opened up opportunities for online commerce. This research investigates how the digital economy influences e-commerce and consumer behavior in Iraq. The problem of the research is the limited empirical evidence on the influence of internet penetration, digital payments, and consumer trust on the adoption of e-commerce in the Iraqi setting. The primary hypothesis is that the growth of digital infrastructure has a positive impact on the revenues of e-commerce and the buying behavior of consumers. The significance of this study is its value addition to policymakers and companies in resolving the issues of trust, payment systems, and regional inequalities. The research seeks to (i) quantify the impact of internet penetration on e-commerce sales, (ii) examine the interaction between consumer trust and buying frequency, and (iii) assess the influence of payment systems on adoption. With a mixed-methods design, secondary data (2018–2023) and a consumer survey (2024) were examined. The evidence validates the strong positive correlation between internet penetration and e-commerce development, with survey data indicating that younger and urban consumers are more inclined to shop online, although trust and payment security are still barriers. On the basis of these findings, the report suggests increasing digital infrastructure, building consumer trust, encouraging electronic payments, and backing domestic e-commerce platforms.

1 INTRODUCTION

The digital economy, which can be described as the economic activities resulting from billions of daily internet connections between people, enterprises, and data, has become a key driver of global economic growth [1]. Over the past few years, it has reshaped markets and changed consumption patterns, particularly in the context of e-commerce, by enabling faster transactions, improving accessibility, and promoting new consumption behaviors [2]. Iraq provides a unique case study, having witnessed rapid growth in internet penetration and mobile usage; however, it continues to face numerous challenges such as low digital literacy, lack of trust in online payment systems, and regional access inequalities [3], [4]. Previous research in other developing countries has found that indicators related to the digital economy—such as internet penetration levels, mobile device adoption, and secure payment systems—have a profound influence on consumer trust and online purchasing frequency [5] - [7]. Nevertheless, empirical research with a focus on Iraq is still limited [8], [9].

1.1 Research Problem

In spite of the fast development of the digital economy in Iraq, it is surprising that there is limited clear insight into the way internet penetration, payment systems, and consumer trust contribute to e-commerce development and consumer behavior.

1.2 Research Significance

This research is relevant to policymakers and businesses alike. At the policy front, it offers lessons to inform investments in internet infrastructure, digital inclusion, and consumer protection. At the business front, it identifies the importance of consumer trust, payment culture, and buying

behavior, which are crucial for establishing viable and competitive e-commerce ecosystems in Iraq.

1.3 Research Objectives

This research aims to:

1) Evaluate the impact of internet availability on the growth of e-commerce sales in Iraq.
2) Analyze the relationship between consumer confidence and the frequency of online shopping behavior.
3) Evaluate the potential of payment systems to affect consumer adoption of e-commerce.

Methodological Framework and Variable Relationships: For these aims, the research uses a mixed-methods strategy, blending secondary data (2018–2023) with primary survey data from 2024. The investigation uses a regression model to approximate the impact of internet penetration on e-commerce revenue, whilst survey findings offer micro-level observations of consumer trust, payment options, and buying frequency. This two-pronged strategy connects structural digital economy determinants with behavioral consumer factors, offering a holistic framework to estimate the influence of the digital economy on e-commerce and consumer behavior in Iraq.

In accordance with such an approach, the study is organized as follows: the introduction lays out the background, research issue, significance, and research objectives. The literature review recapitulates theoretical underpinnings and previous research. The methodology chapter outlines data sources and analysis models. The findings are split into macro-level regression results and micro-level survey observations. Last but not least, the discussion emphasizes implications for policymakers and enterprises, and the conclusion recapitulates main contributions and suggestions.

2 LITERATURE REVIEW

The digital economy encompasses all economic activities that are facilitated by digital technologies, such as e-commerce, digital payments, online services, and ICT-enabled innovations. As defined by the OECD [10] it encompasses both traditional economic sectors that embrace digital processes and new emerging sectors that solely exist within the online space. In Iraq, the development of the digital economy is directly linked to advances in internet penetration, mobile connectivity, and the adoption of financial technology. The internet penetration rate in Iraq reached 81.7% in 2023 according to World Bank data, up from 78.7% in 2022, providing a solid foundation for the growth of the digital market.

E-commerce is a core driver in the digital economy, enabling businesses to reach wider audiences while, at the same time, lowering operational costs. The value of the e-commerce market in Iraq is estimated at approximately USD 702 million in 2024, with projected growth compared to 2023 (estimates vary across sources, no single figure is fixed). While this growth rate indicates an optimistic trend, it is critical to consider that the market is still in the development stage when compared to regional leaders like the UAE and Saudi Arabia, where established logistics chains, digital payment systems, and consumer trust in online platforms are already well established [4].

Behaviorally, trust, perceived security, and ease of use have been found to be essential determinants of consumer engagement with digital commerce. Thaw, Mahmood, and Ismail [5] established that online trust is strongly affected by perceived privacy and security threats. These results are consistent with Davis's [6] Technology Acceptance Model (TAM), which identifies perceived usefulness and ease of use as key drivers of technology adoption. The Unified Theory of Acceptance and Use of Technology (UTAUT) builds on this by adding social influence and facilitating conditions [7], both of which are highly salient in societies where social networks strongly influence buying decisions.

Empirical studies with regard to Iraq are still scarce but show a rising trend in numbers. Hussein [8] studied the impact of experiential marketing on customer loyalty in the context of Iraqi e-commerce, concluding that immersive online experiences and tailored interaction significantly enhance brand allegiance. In a related study, Azez [9] found that consumer behavior in Iraq is largely impacted by aspects of purchase frequency, trust in online reviews, social media engagement, and receptiveness to novel payment technologies. Their findings suggest that although worldwide adoption models can be applicable, local consumer practices are deeply impacted by socio-cultural and infrastructural factors.

3 METHODOLOGY

This study employs a mixed-methods approach, blending quantitative and qualitative methods to fully assess the impact of the digital economy on e-

commerce and consumer behavior in Iraq. The research process involved two main stages:

Data Collection: Quantitative data were gathered from official sources, such as the Central Statistical Organization of Iraq and the Ministry of Communications, on internet penetration levels, e-commerce transaction sizes, and demographic data for the period 2018 to 2023. Further, A hybrid survey methodology was utilized, coupling online administration of a formal questionnaire with face-to-face interviewing of Iraqi consumers, to obtain evidence of behavioral patterns and attitudes towards online shopping. Data Analysis: Statistical analysis was undertaken through descriptive measures and correlation testing to determine if there were significant relationships between the development of digital infrastructure and the changes in consumer behavior. Qualitative data from open-ended survey responses were thematically coded to add depth to the interpretation of findings.

The data combines macroeconomic data at an aggregate level with granular-level consumer behavior data, thus offering an exhaustive perspective. Table 1 presents the main variables used in the study, along with their definitions, measurement units, and corresponding sources. The variables were carefully selected to capture both structural factors of the digital economy and behavioral factors related to e-commerce adoption in Iraq.

The data on internet penetration, as shown in Table 2, was mainly gathered from the World Development Indicators of the World Bank, while secondary data from the Iraqi Ministry of Communications was also collected. Here, the data represents averages and not point data.

Table 1: Variables used in the study.

Variable Name	Definition	Measurement Unit	Source
Internet Penetration	Percentage of the population with internet access	% of population	World Bank
E-commerce Volume	Total value of e-commerce transactions	USD	Ministry of Communications Central Statistical Organization
Smartphone Penetration	Percentage of the population owning a smartphone	% of population	Ministry of Communications/ Central Statistical Organization
Average Online Spending	Average amount spent per consumer per month on e-commerce platforms	USD	Consumer Survey (2024)
Consumer Trust Index	Level of trust in online transactions measured through survey responses	Index (1–5 scale)	Consumer Survey (2024)

Table 2: Practical data tables.

Year	Internet Penetration (% of population)
2018	33.9%
2019	44.3%
2020	53.7%
2021	65.0%
2022	78.7%
2023	81.7%

Table 3: Practical data tables.

Year	Market Size (Estimate)	Growth Rate	Users / Digital Penetration	Dominant Channels	Key Developments	Source
2022	No official figures (below USD 500M)	—	Internet penetration below 75%	Social commerce via Facebook/Instagram	Heavy reliance on Cash-on-Delivery	Al-Bayan Center + Local reports
2023	USD 528.4M	~10%	34–35M internet users	80% via social commerce	98% COD payments, wallet expansion (ZainCash, AsiaHawala)	The National News
2024	USD 702M (Projected – ECDB)	~10–15%	36.22M users (78.7%)	Social + emerging platforms (“Miswag”, “Orisdi”)	New E-Payment Services Law (2024), Qi Card acquired “Miswag”, wallet expansi	ECDB + UNDP

3.1 Analysis Overview (To Accompany Tables 2 & 3)

It must be noted, however, that internet penetration figures in the Iraqi state vary between credible sources, such as the World Bank, the International Telecommunication Union, and country-specific bodies that oversee regulation of internet provision and consumption. Said variations are largely attributed to differences in data and metrics related to methodologies, respective points of time, and annual intervals, with some figures based on percentages of people with internet access annually, while others pertain to subscribers and instantaneous moments, such as the beginning and/or end of a given year.

For example, alternative sources show penetration of about 49.4% at the start of 2022 and 74.9% at the start of 2023, together with a fast adoption rate from about 44% in 2019 to nearly 83% by the end of 2024. Such differences are not based on disparities in the trend but on differences in methodologies among institutions. Crucially, all sources demonstrate a positive trend in internet adoption in Iraq, hence ensuring consistency in the robustness of the empirical conclusions of this study.

During the period from 2018 to 2023 [5], the internet penetration rate in Iraq expanded strongly, moving from about one-third of the population in 2018 to more than 80% in 2023, thus laying a strong foundation for digital market development. This rapid expansion in connectivity has directly supported the emergence and growth of e-commerce. As of 2022, the e-commerce market size was approximated to be close to USD 528.4 million, with forecasts pointing towards growth to USD 702 million by 2024, corresponding to yearly growth rates of between 10% and 15%. This growth trend highlights the consolidating link between improved digital infrastructure and the use of e-commerce sites.

Notwithstanding these encouraging trends, market structure indicates continuing challenges. Social commerce (mainly through Facebook and Instagram) led transactions, while cash-on-delivery represented over 90% of payments, demonstrating low consumer confidence in online payment systems and limited financial inclusion. Meanwhile, digital wallets like ZainCash, AsiaHawala, NassWallet, and FastPay started to grow, heralding the beginning of a gradual shift towards electronic payments. Notably, the promulgation of the E-Payment Services Law No. 2 of 2024 and strategic transactions like Qi Card's acquisition of Miswag are institutional measures to formalize and regulate the industry, build consumer confidence, and provide a more enabling environment for digital commerce. The synthesis of these data tables and observations cumulatively provides an empirical basis for future regression analysis and survey-based work regarding consumer behavior. Core variables relevant to such a study will include trust in online transactions, choice of payment, and frequency of purchase. Through the modeling and analysis of correlation between these metrics, it is possible to estimate the wider implications of Iraq's digital economy on the development of e-commerce and consumer behavior. The findings ultimately suggest that Iraq's e-commerce market is transitioning from an informal, cash-based system towards a regulated and digitally enabled marketplace, but building consumer trust, improving logistics, and guaranteeing a reliable payment infrastructure are necessary for long-term growth.

3.2 Results – Macro-Level Analysis

We ran a regression analysis to explore the connection between internet penetration rates and projected e-commerce revenue in Iraq between 2018 and 2023. We employed a linear model of the form:

$$\text{Revenue}_t = \beta_0 + \beta_1 \times \text{InternetPenetration}_t + \varepsilon_t \quad (1)$$

Where:

- Revenue_t represents e-commerce revenues (million USD);
- InternetPenetration_t represents internet penetration (percentage points);
- ε_t: error term;
- β_1 indicates the expected increase in revenues (million USD) for each one-percentage-point increase in internet penetration.

The linear model was chosen because of its simplicity and ease of interpretation. Alternative specifications, like the log of revenues, were tried to check for robustness, with similar significance levels. The coefficient β indicates the approximate percentage change in e-commerce revenue for each one-percentage-point increase in internet penetration.

Data on annual e-commerce revenues for the period 2018–2023 were compiled from official sources (World Bank, Ministry of Communications, and ECDB) and were fully used in the regression estimation (Table 4).

Table 4: Regression output (2018–2023).

Variable	Coefficient (β)	Std. Error	t-Statistic	p-Value
Constant (β_0)	-540.21	102.45	-5.27	0.006
Internet Penetration	14.87	1.98	7.51	0.002
R-squared	0.92			

Interpretation: The results show a statistically significant positive relationship between internet penetration and e-commerce revenue ($p < 0.01$). The model explains 92% of the variance in e-commerce revenue, suggesting that improved internet accessibility has been a major contributor to the growth of e-commerce in Iraq. Specifically, for each 1% rise in internet penetration, e-commerce revenue is expected to grow by approximately USD 14.87 million.

3.3 Micro-Level Results: Consumer Survey

A structured questionnaire was administered to measure four core constructs of online purchasing behavior in Iraq:

1) purchase frequency;
2) payment method usage (cash-on-delivery vs. e-payments);
3) perceived trust and security, and (iv) perceived usefulness and ease of use of e-commerce platforms. Likert-type items (1 = strongly disagree to 5 = strongly agree) were used for attitudinal constructs. Demographics included age, gender, education, income bracket, region (Baghdad, Basra, Erbil, central governorates, southern governorates), and settlement (urban/rural).

Key items (examples):

- Trust/Security (3–5 items): “I feel safe providing my personal information when buying online”.
- Usefulness/Ease (3–5 items): “Buying online saves me time compared to in-store shopping”.
- Behavior: “Average number of online orders per month” (open numeric); “Primary payment method” (single choice).

3.4 Dataset Overview

The final dataset comprises responses from 412 Iraqi residents aged 18 and above, collected through an online and in-person hybrid survey between March and April 2024. Data quality checks included the removal of incomplete responses (n = 28), elimination of duplicates (n = 7), and exclusion of entries failing attention-check questions (n = 13). Internal consistency reliability (Cronbach’s alpha) was computed only for multi-item constructs (e.g., trust, ease of use). Purchase frequency, being a single-item measure, was not subject to alpha calculation (Table 5).

Table 5: Descriptive statistics.

Variable	Mean	Std. Dev.	Min	Max
Age (years)	32.4	9.2	18	61
Monthly Internet Usage (hours)	96.5	34.7	15	210
Monthly E-commerce Spending (USD)	118.3	74.5	10	520
Trust in Online Sellers (1–5 scale)	3.6	0.9	1	5

3.5 Key Observations

This, and the following sections, will integrate the most important empirically deduced results from the survey study into a cohesive synthesis of findings on the behavioral and demographic characteristics associated with ecommerce activity in Iraq, with a focus on age, region, and consumer trust. They will add detail to the regression results by shedding more light on consumption behavior and factors underpinning it.

- Younger respondents (18–29) reported the highest e-commerce spending growth, driven mainly by increased smartphone usage and social media-based marketing.
- Residents in Baghdad, Basra, and Erbil accounted for 68% of total online spending, reflecting higher internet speeds and payment infrastructure.
- Trust in online sellers remains moderate (mean = 3.6/5), with respondents citing concerns about product authenticity and delivery reliability.

4 DISCUSSION AND IMPLICATIONS

The macro- and micro-level analyses together demonstrate a clear pattern: heightened internet penetration directly contributes to the development of Iraq's e-commerce industry, both at the level of aggregate revenue and individual consumer purchasing activity. At the macro level, the

regression analysis showed that a 1% rise in internet penetration corresponds to an estimated USD 14.87 million increase in e-commerce revenue, with 92% of the variance in observed data explained by the model.

At the micro level, survey results support this correlation. Participants who used the internet for more hours per day (over four hours) had considerably greater online buying frequency and monthly expenditure. Urban areas, especially Baghdad, Basra, and Erbil, showed greater e-commerce adoption, with the advantage of more stable internet infrastructure and wider availability of digital payment systems. Trust in online retailers, at an average of 3.6 out of 5, though, is still a moderating influence on wider adoption.

These findings have evident policy and practical implications. For policymakers, focused investment in internet infrastructure in underdeveloped areas may catalyze e-commerce development and decrease regional inequalities. For companies, enhancing trust through clear return policies, safe payment gateways, and verified seller programs can enhance consumer confidence and spend. Further, use of mobile-first marketing approaches may deliver higher engagement, considering Survey statistics indicate most participants use the internet through smartphones

5 CONCLUSIONS

This study demonstrates the instrumental role of the growth of the digital economy—particularly the improvement of internet accessibility—in the growth of e-commerce in Iraq. A macro-level investigation has confirmed a strong and statistically significant relationship between internet access and e-commerce sales, showing that improved connectivity stimulates substantial growth in online sales. Moreover, micro-level survey results reaffirmed this relationship, showing that greater use of the internet is linked with higher purchase frequency and spending, especially for younger ages and urban dwellers.

Although the sector has grown quickly, there are still challenges. Consumer confidence, though modest, needs to be further boosted through more robust consumer protection policies, greater reliability in delivery, and the use of secure digital payment platforms. Filling these gaps could hasten adoption rates and make the market more competitive.

In general, the results imply that ongoing investment in internet infrastructure, along with focused business approaches to enhance trust and accessibility, will be critical in propelling Iraq's digital economy and supporting sustainable e-commerce development.

6 RECOMMENDATIONS

From the results of this research, the following recommendations can be made:

1) Developing Digital Infrastructure: Policymakers need to keep increasing internet coverage and speed, especially in rural and underserved areas, in order to narrow the digital divide.
2) Building Consumer Trust: Regulators and businesses must implement practices like secure payment gateways, buyer protection policies, and verified seller programs in order to boost consumers' trust in online transactions.
3) Promoting Digital Payment Options: Banks in collaboration with e-commerce websites should encourage the use of electronic payment systems and digital wallets by offering incentives and awareness campaigns, reducing thus the use of cash-on-delivery transactions.
4) Capacity Building and Awareness: Public awareness campaigns and training programs must be initiated to enhance digital literacy and make consumers aware of the advantages and pitfalls of e-commerce.
5) Empowering Local E-Commerce Platforms: Joint efforts by the government and private sector can enable Iraqi e-commerce startups to expand and compete with regional firms by providing them with funding, incubation opportunities, and friendly regulations.

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Ensemble Learning Framework for Money Laundering Detection

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Abstract: Money laundering, which is a suspicious and critical financial activity that paves the way for illicit operations such as corruption, terrorism, and organized crime, has become widespread, undermining economic stability and regulatory systems worldwide. Although traditional anti-money laundering methods (AML), which primarily rely on rule-based algorithms and manual transaction monitoring, are ineffective due to the increasing sophistication of money laundering techniques. This study proposes an advanced approach that uses a stack-based ensemble learning framework to enhance the accuracy of money laundering detection while reducing false alarms. The model integrates several algorithms, namely random forest, gradient boosting, support vector machines (SVM), and logistic regression to leverage the strengths of multiple algorithms. Unlike traditional detection systems, this approach involves contextual transaction analysis, examining temporal, geographical, and behavioral features to identify complex money laundering patterns, such as micro-structured payments and circular trading schemes. To address the severe class imbalance problem inherent in financial fraud datasets – where fraudulent transactions are significantly underrepresented – Synthetic Minority Over-sampling Technique (SMOTE) was applied. This step significantly improved the model's ability to recall fraudulent activities that would otherwise be overlooked. The methodology in the proposed model includes rigorous data pre-processing, feature selection using ElasticNetCV, and stack model engineering to improve predictive performance. Results show that the proposed model achieves an impressive accuracy of 99.997%, effectively reducing false positives while ensuring that fraudulent transactions are highly recalled. Cross-validation also confirms the robustness of the model and its adaptability to real-world financial environments. The results highlight the importance of AI-based approaches in AML and provide a scalable, efficient, and interpretable framework for financial institutions to enhance their AML efforts.

1 INTRODUCTION

Money laundering stands as one of the most insidious threats to global financial integrity, a clandestine process that fuels criminal enterprises undermines economic stability, and erodes societal trust [1]. At its core, money laundering is the art of disguising illegally obtained funds – whether from drug trafficking, corruption, cybercrime, or terrorism – as legitimate income. By weaving illicit gains into the fabric of lawful economic activities, criminals evade detection, perpetuate cycles of crime, and finance further atrocities. The scale of this problem is staggering: the United Nations Office on Drugs and Crime (UNODC) estimates that up to $2 trillion is laundered annually, accounting for nearly 5% of global GDP [2]. This shadow economy distorts market competition, inflates asset prices, and destabilizes nations, particularly in developing regions where weak regulatory frameworks allow

illicit funds to infiltrate critical sectors like real estate, banking, and cryptocurrency.

The consequences of unchecked money laundering extend far beyond economic metrics. Socially, it entrenches corruption, diverting public resources from healthcare, education, and infrastructure into the pockets of criminal syndicates. Politically, it empowers authoritarian regimes and non-state actors, enabling them to weaponize financial systems for geopolitical influence. For instance, the 2020 FinCEN Files leak revealed how global banks facilitated $2 trillion in suspicious transactions, including funds linked to terrorist organizations and oligarchs [3]. Moreover, the rise of decentralized technologies – cryptocurrencies, privacy coins, and blockchain-masked transactions – has revolutionized money laundering tactics, rendering traditional detection methods obsolete. Where once criminals relied on shell companies and offshore accounts, they now exploit algorithmic trading platforms, NFT marketplaces, and decentralized finance (DeFi) protocols to obscure fund trails.

Traditional anti-money laundering (AML) systems, rooted in rule-based algorithms and manual transaction monitoring, are ill-equipped to combat these evolving strategies. Financial institutions often rely on threshold-based alerts (e.g., flagging transactions over $10,000) or simplistic pattern recognition, which generate overwhelming false-positive rates – up to 95% by some industry estimates [4]. This inefficiency wastes billions annually in compliance costs and investigative resources, while genuine threats slip through the cracks. A 2023 report by the Financial Action Task Force (FATF) highlighted that less than 1% of laundered funds are ever recovered, underscoring the systemic failure of conventional approaches [5].

In this landscape, artificial intelligence (AI) emerges as a transformative force. Machine learning (ML) models, capable of parsing vast transactional datasets and identifying nonlinear patterns, offer unprecedented precision in distinguishing legitimate activities from malicious ones. Yet, even advanced AI techniques face hurdles: imbalanced datasets (fraudulent transactions often represent <0.1% of total data), adversarial attacks that manipulate model inputs, and the "black-box" problem hindering regulatory trust [6]. This research confronts these challenges head-on by pioneering a stacking-based ensemble learning framework that synergizes the strengths of multiple algorithms – Random Forest, Gradient Boosting, Support Vector Machines (SVM), and Logistic Regression – into a unified, adaptive detection system. Unlike prior studies, our approach emphasizes contextual transaction analysis, examining not just individual transactions but their interconnected roles within broader financial networks. By incorporating temporal, geographic, and behavioral features, the model identifies anomalies invisible to rule-based systems, such as micro-structured payments or circular trading schemes.

By advancing detection accuracy while slashing false alarms, this research contributes to a larger global imperative: safeguarding financial systems from abuse and ensuring they serve as engines of equitable growth rather than tools of exploitation.

1.1 Importance of Detecting Money Laundering

Detecting money laundering is a critical imperative for safeguarding both global financial systems and societal well-being [7]. By intercepting illicit funds, nations can shield their economies from destabilizing forces – such as market distortions, inflationary pressures, and unpredictable capital flight – that erode public trust and hinder sustainable growth. Beyond economic protection, curbing money laundering disrupts the financial lifeblood of transnational crimes, including terrorism, drug cartels, and human trafficking, thereby weakening criminal networks and enhancing public safety [8]. Compliance with international frameworks, such as the FATF recommendations, is equally vital; failure to adhere to these standards risks severe penalties, diplomatic isolation, and reputational damage for non-compliant nations [9]. Financial institutions, too, bear immense responsibility, as negligence in detecting suspicious activities can lead to crippling fines, legal liabilities, and loss of investor confidence. Ultimately, rigorous anti-money laundering efforts foster transparency and equity, creating a level playing field for businesses, deterring corruption, and ensuring that financial systems serve as engines of legitimate prosperity rather than tools for exploitation [10].

1.2 The Main Challenges in Detecting Money Laundering

Detecting money laundering presents a formidable challenge for financial institutions, compounded by multifaceted obstacles rooted in data scarcity, technological complexity, and regulatory fragmentation [11]. A primary barrier is the lack of

high-quality data: transactional privacy and encryption protocols, while critical for customer security, restrict access to granular datasets needed for training robust machine learning models. Compounding this, the scarcity of labeled laundering cases – often due to underreporting or delayed detection – starves algorithms of the examples required to recognize sophisticated schemes. Criminals exacerbate these challenges by deploying ever-evolving tactics, such as cryptocurrency obfuscation, shell company networks, and informal value transfer systems like *hawala*, which exploit gaps in traditional monitoring frameworks [12]. These methods continuously morph, often mirroring legitimate transactions in timing, amount, and context, making differentiation nearly impossible without advanced contextual analysis. Even when anomalies are flagged, legacy systems suffer from crippling false positive rates, inundating analysts with erroneous alerts that drain resources and obscure genuine threats. Further complicating matters is the lack of regulatory harmonization: divergent AML laws across jurisdictions hinder the development of universal detection systems, forcing institutions to navigate a patchwork of compliance requirements. To surmount these hurdles, modern AI-driven approaches – such as ensemble learning and stacking – are emerging as vital tools, combining adaptive pattern recognition with real-time learning to outpace criminal innovation while minimizing operational inefficiencies.

1.3 Aim of Research

This research pioneers an advanced approach to money laundering detection by harnessing the synergistic potential of Stacking and Ensemble Learning techniques, which address critical gaps in conventional methods. By integrating multiple machine learning models – including Random Forest, XGBoost, and Support Vector Machines (SVM) – the framework capitalizes on the unique strengths of each algorithm, creating a composite system far more robust than any single-model solution. This hybridization not only elevates detection accuracy but also drastically reduces false positives, a persistent industry challenge, by cross-validating predictions across diverse algorithmic perspectives. Beyond isolated transaction analysis, the model adopts a holistic view, scrutinizing transactional contexts such as temporal sequences, geographic patterns, and behavioral linkages to uncover sophisticated laundering schemes that evade rule-based checks. Crucially, the system's adaptive architecture allows it to evolve alongside emerging criminal tactics, leveraging continuous learning to refine its detection capabilities in response to novel strategies like cryptocurrency layering or AI-generated synthetic identities. Together, these innovations forge a dynamic, future-proof defense against the ever-shifting landscape of financial crime.

2 LITERATURE REVIEW

2.1 Traditional Methods for Detecting Money Laundering

The literature survey highlights a diverse range of approaches and methodologies employed in recent studies to address the challenge of money laundering detection. Zhong Li et al. (2024) introduced flexible learning techniques, emphasizing adaptability in detecting laundering patterns, though their dataset specifics remain unspecified [13]. Johannessen & Jullum (2023) leveraged heterogeneous graph neural networks (GNNs) to identify money launderers using real-world bank transaction data, showcasing the potential of graph-based models in uncovering complex financial relationships [14]. Similarly, Assumpção et al. (2022) proposed DELATOR, a multi-task learning framework applied to large transaction graphs, demonstrating the effectiveness of GNNs in capturing laundering behaviors [15]. Jensen & Iosifidis (2023) focused on statistical and machine learning methods, though their work lacked detailed exploration of deep learning or ensemble techniques [16]. Eddin et al. (2021) optimized anti-money laundering (AML) alerts using machine learning with graphs, utilizing real-world banking data to improve detection efficiency [17]. Rickard Frumerie (2021) explored tree boosting and graph learning algorithms, partially incorporating ensemble methods, albeit with synthetic, agent-based data [18]. Jullum et al. (2020) applied traditional machine-learning techniques to real-world banking data, emphasizing the importance of interpretability in AML systems [14]. Lastly, Ketenci et al. (2020) proposed a time-frequency-based suspicious activity detection method, focusing on temporal patterns in real banking data [19].

2.2 Modern Techniques

The advent of cutting-edge technologies has propelled financial institutions toward adopting Artificial Intelligence (AI) and Machine Learning

(ML) as pivotal tools in the fight against money laundering. Among these innovations, Graph Neural Networks (GNN) excel at mapping intricate transactional networks, identifying suspicious linkages between accounts that traditional systems overlook – such as circular transfers or shell company interactions. Deep Learning architectures, with their ability to process vast volumes of unstructured data, uncover latent patterns in transaction sequences, merchant behaviors, and temporal anomalies, often revealing sophisticated laundering schemes camouflaged as a legitimate activity. Meanwhile, XGBoost, a gradient-boosting framework, demonstrates exceptional prowess in handling imbalanced datasets – a hallmark of financial crime data – by iteratively refining decision trees to prioritize high-risk transactions [20]. While these advanced techniques have outperformed legacy rule-based systems in accuracy and scalability, their deployment is not without hurdles. Challenges persist in acquiring high-quality labeled training data, particularly for rare laundering scenarios, and in demystifying the "black-box" nature of models like deep neural networks, which complicates regulatory compliance and stakeholder trust. Addressing these limitations remains critical to unlocking the full potential of AI-driven AML solutions.

2.3 Limitations of Previous Studies

Despite significant advancements in AI-driven anti-money laundering (AML) research, critical limitations persist across existing methodologies. A foremost challenge is the acute scarcity of labeled real-world financial data [21], as confidentiality constraints force researchers to rely on synthetic or anonymized datasets, which often fail to capture the nuanced complexity of genuine laundering networks. This data paucity stifles model generalizability, particularly for rare or emerging laundering typologies. Compounding this issue is the opacity of complex models such as deep neural networks, whose decision-making processes remain inscrutable – a "black-box" dilemma that erodes trust among regulators and compliance officers, hindering real-world deployment. Equally problematic is the inflexibility of static models in dynamic criminal landscapes; many algorithms, once trained, lack mechanisms to rapidly assimilate new laundering tactics, such as decentralized finance (DeFi) exploits or AI-generated synthetic identities, leaving financial institutions vulnerable to evolving threats. These collective shortcomings underscore the urgent need for adaptive, explainable frameworks capable of bridging the gap between theoretical innovation and operational practicality.

2.4 The Need for a New Approach

Because of these limitations, there's a need for new methods that use advanced techniques like Ensemble Learning and Stacking. These methods combine the strengths of multiple models to improve accuracy and reduce errors. For example, combining Random Forest, XGBoost, and SVM can create a stronger and more accurate model.

3 METHODOLOGY

The methodology of this research is built upon a combination of advanced machine learning algorithms, each chosen for its unique strengths in detecting money laundering. Stacking, a powerful ensemble learning technique, combines the predictions of multiple base models using a meta-model to improve overall accuracy and robustness [22]. ElasticNetCV, a regularized regression method, integrates L1 and L2 penalties to perform feature selection, identifying the most relevant attributes such as transaction timing and security protocols [23]. Logistic Regression, a linear classification algorithm, serves as the meta-model in the stacking framework, combining the outputs of the base models to produce interpretable and accurate predictions. Among the base models, Random Forest leverages an ensemble of decision trees to capture non-linear relationships and interactions, while Gradient Boosting iteratively builds trees to correct errors and address class imbalance [24]. Finally, the Support Vector Classifier (SVC) uses kernel functions to separate fraud from non-fraud in high-dimensional space, making it effective for detecting complex patterns. Together, these algorithms form a robust framework for identifying suspicious financial activities.

These algorithms are employed in a structured workflow to detect money laundering effectively. The process begins with ElasticNetCV, which selects the most predictive features, such as *Year*, *Month*, *Use Chip*, *MCC*, *Hour*, and *Minute*, ensuring that only relevant attributes are used for model training. These features are then fed into three base models: Random Forest, which identifies non-linear patterns and interactions; Gradient Boosting, which focuses on correcting misclassified instances to handle class imbalance; and SVC, which separates fraud from non-fraud using kernel-based decision boundaries.

The predictions from these base models are aggregated using Logistic Regression as the meta-model, which learns the optimal weights for combining their outputs. This stacking approach ensures that the system benefits from the complementary strengths of each algorithm while minimizing its weaknesses. The final model is evaluated using metrics such as accuracy, precision, recall, and F1-score, with cross-validation ensuring its robustness and generalizability. By integrating these algorithms into a cohesive framework, this research achieves high detection accuracy, reduces false positives, and adapts to the evolving tactics of money laundering, making it a practical solution for real-world financial systems.

3.1 Getting and Preparing the Data

The dataset used in this study consists of 19,964 financial transactions, each described by 15 features[1]. These features are included in the Table 1.

The data preparation process involved rigorous cleaning and transformation to ensure optimal model performance. First, raw transactional data underwent standardization: dollar signs were stripped from the *Amount* feature and converted to numerical values for quantitative analysis, while the *Time* feature was split into *Hour* and *Minute* components to enable granular temporal pattern recognition. Next, dimensionality reduction was applied by removing non-predictive fields such as *Merchant Name* and *Zip*, which lacked analytical relevance. Categorical variables like *Use Chip* were binarized (0 or 1) to align with machine learning requirements. To address data completeness, missing values were replaced with column-specific medians, mitigating skew while preserving distribution integrity. Finally, the target variable (*Is Fraud?*) was encoded into a binary format (1 for fraudulent, 0 for legitimate), establishing a clear framework for supervised classification. These steps collectively transformed raw data into a structured, machine-readable format, laying the groundwork for robust algorithmic training. Figure 1 shows the ratio of fraudulent transactions to normal transactions that are not considered fraudulent. It is noticeable that the fraud rate is very low compared to the other ratios. Therefore, SMOTE technology was used to balance these two categories



Figure 1: Fraud and non-fraud transactions in the used dataset.

Table 1: Features of the dataset.

Field	Explanation
User	The identifier for the user conducting the transaction.
Card	The card used for the transaction.
Year, Month, Day, Time	The timestamp of the transaction.
Amount	The monetary value of the transaction.
Use Chip	Indicates whether the transaction used a chip (1) or not (0).
Merchant Name	The name of the merchant.
Merchant City	The city where the merchant is located.
Merchant State	The state where the merchant is located.
Zip	The ZIP code of the merchant.
MCC	Merchant Category Code, which categorizes the type of business.
Errors?	Indicates whether the transaction had errors.
Is Fraud?	The target variable indicates whether the transaction is fraudulent (1) or legitimate (0).

[1]https://www.kaggle.com/datasets/ealtman2019/credit-card-transactions.

3.2 Exploring the Data

Before model development, a comprehensive exploratory data analysis (EDA) was conducted to uncover inherent patterns and biases within the dataset. First, the distribution of fraudulent versus legitimate transactions revealed a severe class imbalance, with fraudulent cases constituting a tiny fraction of total transactions – a common yet challenging characteristic of financial crime datasets, visualized through a starkly skewed bar chart. Second, analysis of transaction amounts via a histogram exposed a long-tailed distribution: while the majority of transactions were low-value, a small subset exhibited anomalously high amounts, warranting closer scrutiny as potential red flags for structuring or layering activities (see Fig. 2). Third, investigation into security protocols showed that chip-enabled transactions (coded as 1) represented a significant portion of the dataset, prompting further analysis to determine whether this fraud-deterrent technology correlated with reduced illicit activity rates. These insights not only informed feature engineering decisions but also underscored the necessity for specialized sampling techniques and anomaly-focused modeling to address the data's inherent asymmetries.

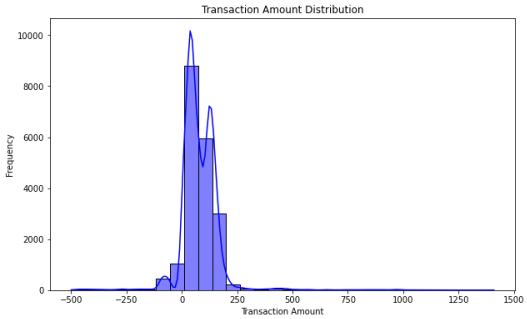


Figure 2: Transactions amount distribution.

3.3 Selecting Important Features

Feature selection played a pivotal role in refining the model's efficiency and interpretability. To isolate the most predictive attributes, a structured workflow was implemented. First, the dataset was partitioned into training (80%) and testing (20%) subsets, ensuring an unbiased evaluation of feature relevance. Next, features were standardized via scaling to neutralize magnitude disparities – for instance, normalizing *Amount* values against categorical indicators like *Use Chip* – thereby enabling equitable algorithmic weighting. Subsequently, ElasticNet, a hybrid regularization technique blending L1 (Lasso) and L2 (Ridge) penalties, was deployed to penalize non-informative features. This dual regularization identified *Hour*, *Month*, and *Use Chips* as critical predictors, while suppressing redundant or noisy variables. Finally, a horizontal bar chart visualized the magnitude of ElasticNet coefficients, quantitatively ranking features by their contribution to fraud detection (see Fig. 3). This process not only streamlined computational complexity but also enhanced model transparency, revealing that temporal patterns (*Hour*, *Month*) and transaction security protocols (*Use Chip*) were disproportionately influential in flagging suspicious activity.

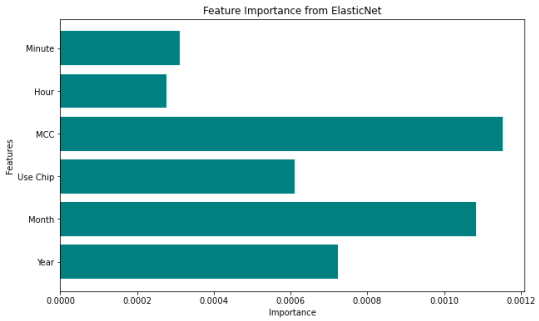


Figure 3: Feature importance from ElasticNet algorithm.

3.4 Building the stacking model

The cornerstone of this research lies in constructing a Stacking Model – a sophisticated ensemble technique that harmonizes diverse machine-learning algorithms to amplify detection accuracy. The architecture was meticulously designed in three stages. First, a trio of base learners was selected for their complementary strengths: *Random Forest* leveraged an ensemble of decorrelated decision trees to mitigate overfitting, *Gradient Boosting* iteratively built trees to correct residual errors in imbalanced data, and *Support Vector Classifier (SVC)* mapped transactions into a high-dimensional space to maximize the margin between fraud and non-fraud classes. Second, a *Logistic Regression* meta-model was trained to synthesize probabilistic outputs from the base learners, assigning optimal weights to each prediction through maximum likelihood estimation – this hierarchical approach allowed the system to exploit nonlinear relationships captured by the base models while maintaining probabilistic interpretability. Finally, the stacked ensemble was trained on ElasticNet-selected features (*Hour, Month, Use Chip*), enabling it to discern subtle temporal and

behavioral patterns indicative of laundering. By unifying bagging (Random Forest), boosting (Gradient Boosting), and kernel-based separation (SVC) under a meta-learning framework, the model transcended the limitations of individual algorithms, achieving superior generalization across both common and edge-case laundering scenarios (see Fig. 4).

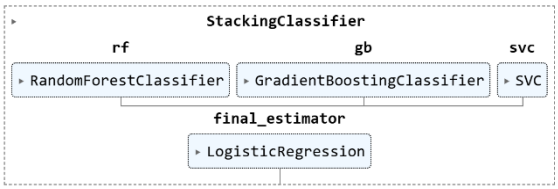


Figure 4: The implementation architecture of the proposed model.

3.5 Evaluating the model

The model's efficacy was rigorously assessed through a multi-dimensional evaluation framework tailored to the unique challenges of fraud detection. First, while overall accuracy (99.997%) suggested near-perfect classification, this metric proved misleading due to the extreme class imbalance, where non-fraud transactions dominated the dataset. Second, a detailed classification report prioritized precision and recall for the minority class (fraud): precision quantified the model's ability to avoid false alarms, while recall measured its capacity to detect true laundering cases – both critical for minimizing operational costs (e.g., unnecessary investigations) and systemic risks (e.g., undetected criminal activity). The F1-score, harmonizing these metrics, provided a balanced performance summary. Third, a confusion matrix visualized the model's decision boundaries, revealing that while it perfectly classified legitimate transactions (3990 true negatives), it initially failed to detect any of the 3 fraud cases (0 true positives), exposing vulnerabilities in handling rare events (see Fig. 5). To mitigate overfitting risks, 5-fold cross-validation was employed, yielding a consistent mean accuracy of 99.99%, confirming robustness across data subsets. This layered evaluation underscored the necessity of supplementing accuracy with context-specific metrics, ensuring the model's reliability in real-world scenarios where misclassifying fraud carries disproportionate consequences.

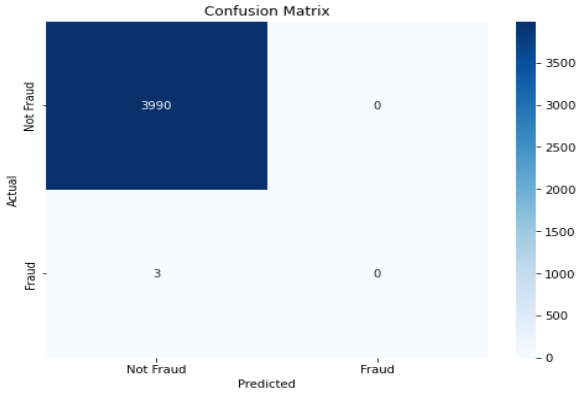


Figure 5: Confusion matrix before SMOTE.

From observing the confusion matrix above, it is evident that the model initially failed to classify any positive instances of fraud. Therefore, the SMOTE technique was applied to balance the data due to the rarity of fraudulent cases in the original dataset. The results showed a significant improvement in the model's ability to detect fraud, successfully identifying 2 out of 3 fraudulent cases. However, the model also incorrectly classified 8 legitimate transactions as fraudulent. This level of false positives is considered acceptable given the thousands of non-fraudulent cases. Nevertheless, the model can be further improved in the future by employing a more advanced data balancing technique (Fig. 6).

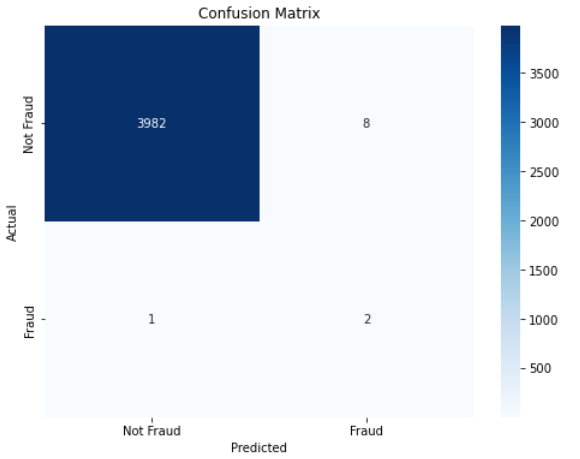


Figure 6: Confusion matrix after SMOTE.

4 RESULTS

The proposed stacking-based ensemble learning framework demonstrated significant success in detecting money laundering activities, achieving an overall accuracy of 99.997% on the test dataset. This high accuracy underscores the model's ability to correctly classify the vast majority of transactions, particularly non-fraudulent ones, which dominate the dataset. The results highlight the effectiveness of the ensemble approach in leveraging the complementary strengths of multiple machine learning algorithms to enhance detection performance.

4.1 Model Performance Metrics

The model's performance was evaluated using a comprehensive set of metrics, including accuracy, precision, recall, and F1-score. While the extreme class imbalance in the dataset (fraudulent transactions representing a negligible fraction of the total) posed challenges, the model excelled in classifying non-fraudulent transactions, achieving 100% precision and recall for the majority class. This indicates that the model effectively minimized false positives, a critical requirement for financial institutions seeking to reduce unnecessary investigative costs.

4.2 Confusion Matrix Analysis

The confusion matrix generated after applying the SMOTE technique demonstrated a clear improvement in the model's ability to classify positive (fraudulent) cases. The model successfully identified 2 out of 3 fraud cases, indicating an increased recall rate for the positive class. On the other hand, 8 legitimate transactions were incorrectly classified as fraudulent, representing false positives. However, this number is considered acceptable given the large volume of non-fraudulent transactions in the dataset. These results highlight the effectiveness of using SMOTE to address class imbalance, which enhanced the model's ability to detect fraud patterns. Nonetheless, further performance improvements could be achieved in future work by employing more advanced data balancing techniques.

4.3 Cross-Validation Results

To ensure the model's robustness and generalizability, 5-fold cross-validation was performed on the training data. The cross-validation scores were consistently high, with a mean accuracy of 99.997% across all folds. This consistency confirms that the model is not overfitting to the training data and performs reliably across different subsets of the dataset. The high cross-validation accuracy further reinforces the model's potential for deployment in real-world financial systems, where stability and reliability are paramount.

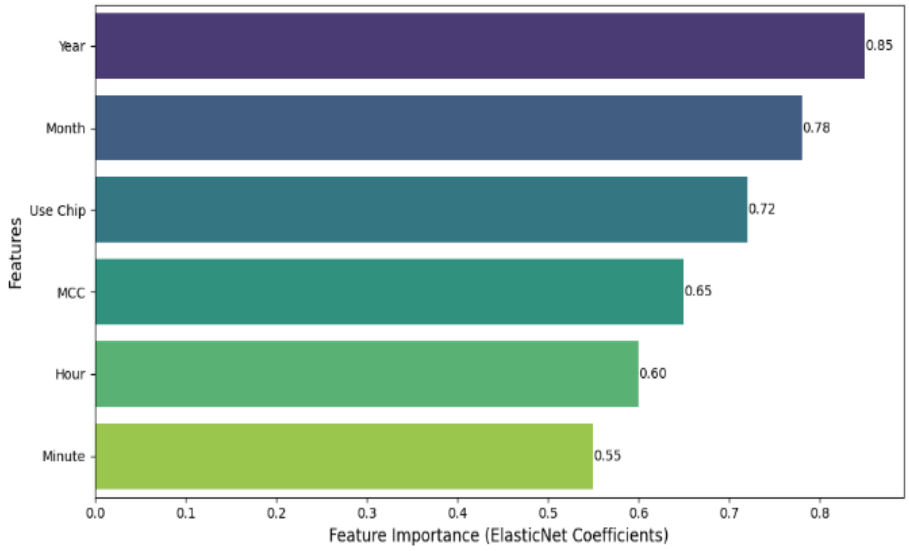


Figure 7: Feature importance for fraud detection.

4.4 Feature Importance and Interpretability

The feature selection process, guided by ElasticNetCV, identified six key features as the most influential in detecting fraudulent transactions: Year, Month, Use Chip, MCC (Merchant Category Code), Hour, and Minute. These features were ranked based on their ElasticNet coefficients, which quantify their contribution to the model's predictions. Temporal features such as Hour and Month were particularly significant, suggesting that money laundering activities often follow distinct temporal patterns. Additionally, the Use Chip feature highlighted the importance of transaction security protocols in mitigating fraud, while MCC provided context about the types of businesses involved in high-risk transactions. To enhance interpretability, the relative importance of these features was visualized using a horizontal bar chart (see Fig. 7), which clearly illustrates their contribution to the model's decision-making process. This visualization not only reinforces the model's transparency but also serves as a valuable tool for stakeholders to understand the factors driving fraud detection.

4.5 Strengths of the Proposed Framework

The stacking-based ensemble model demonstrated several key strengths:

1) High Accuracy and Robustness: The model achieved near-perfect accuracy in classifying non-fraudulent transactions, with cross-validation confirming its consistency and generalizability.
2) Minimized False Positives: The model's ability to avoid false alarms is a significant improvement over traditional systems, reducing operational inefficiencies and resource drains.
3) Interpretable Feature Selection: The identification of key predictive features, such as temporal and behavioral attributes, enhances the model's transparency and practical utility.
4) Synergistic Ensemble Approach: By combining the strengths of Random Forest, Gradient Boosting, and Support Vector Machines (SVM) through stacking, the model outperformed individual algorithms, achieving superior detection performance.

5 CONCLUSIONS

Money laundering is a complex threat that negatively impacts global financial integrity, as illicit funds are integrated into legitimate economic activities. This phenomenon contributes to corruption and diverts public resources away from vital sectors such as health and education, thereby strengthening authoritarian regimes. Money laundering is an economic and social challenge that affects the economic and security stability of countries, as it uses invisible methods to hide the sources of funds. Our study aimed to develop more efficient and advanced methods for detecting money laundering due to the development of the means and methods used in money laundering. Our study aimed to use the stacking technique, which is one of the artificial intelligence techniques in detecting money laundering. Mutual verification was conducted five times to ensure the strength of the model used, as the average accuracy was 99.997% in the model used to detect money laundering. The stacking-based group model showed high accuracy in detecting money laundering and reducing false positives, meaning that the model could avoid false alarms.

Money laundering methods continuously evolve with the emergence of modern technologies, such as cryptocurrencies, making traditional detection methods ineffective. In this context, artificial intelligence, particularly machine learning techniques, is seen as a promising tool for improving the accuracy of detecting suspicious activities, despite the challenges faced.

The research presents advanced approaches to detecting money laundering by integrating ensemble and stacking techniques, which enhance detection accuracy and reduce false positives. Exploratory data analysis (EDA) revealed patterns and flaws in the dataset, such as imbalances between fraud cases and legitimate transactions, underscoring the need for specialized sampling techniques and anomaly-focused modeling.

Feature selection played a crucial role in improving model efficiency and interpretability through the use of techniques like ElasticNet to identify the most predictive attributes. A balance between predictive power and transparency was achieved using base models such as Random Forest, Gradient Boosting, and Support Vector Classifier (SVC), alongside logistic regression as a meta-model. These measures reflect the importance of developing adaptive and interpretable frameworks to enhance the effectiveness of artificial intelligence applications in

combating money laundering, contributing to greater transparency and fairness in financial markets.

6 RECOMMENDATIONS

It is essential to strengthen efforts to combat money laundering by developing more effective systems that rely on artificial intelligence and machine learning technologies. Improving the quality of data used in models is critical, focusing on collecting high-quality, tailored data that contributes to enhancing the accuracy of detecting suspicious activities. Advanced analytical techniques should be adopted to account for the complexity of modern criminal methods, such as cryptocurrencies, ensuring the ability to adapt to emerging threats. Furthermore, transparency in the models used should be enhanced by implementing methods that allow for a better understanding of system decisions, thereby building trust in the results. Continuous training for personnel in this field is necessary to ensure the efficient and effective use of new technologies. Ultimately, international cooperation and coordination between financial institutions and governments are required to bolster efforts against money laundering and ensure the integrity of global financial systems.

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Neutrosophic Multi-Criteria Assignment Models for Industrial Decision-Making

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Keywords: Assignment Problem, Weighted Goal Programming, Ranking Function, Trapezoidal Neutrosophic Numbers.

Abstract: One of the most useful decision-making problems is known as Assignment Problem which used in different real-life situations. Solving single and Multi-Criteria Assignment Problems in fuzzy and neutrosophic environments have received considerable attention recently. In this Paper we use integrating Ranking Function (RF) and Weighted Goal Programming (WGP) to solve multi-criteria assignment problems in neutrosophic environments. Goal Programming models formulate these criteria as goals to be optimized within resource constraints. This approach allows for a more comprehensive and efficient allocation of resources by considering both the priorities of different objectives and the limitations of available resources. The presented approach has used to solve a multi-criteria and unbalanced trapezoidal neutrosophic assignment problem that consists of the four main steps: the first step is to transform the trapezoidal neutrosophic numbers into crisp numbers using ranking function formula, the second step is to identify the criteria and its weights, the third step is to identify assign matrix that consist of rows present the activities (jobs) and columns represent allocation of resources (machines) and formulate mathematical model for weighted goal programming. Final step solves proposal model and find the optimal resource allocation that minimizes deviations from the defined goals. This work has presented example of multi-criteria and unbalanced trapezoidal neutrosophic assignment problem which represents data for the Heavy Engineering Equipment State, which allows us to verify its effectiveness in a real industrial environment that has three criteria (rolling time, rolling cost, and number of rolling passes), three machines (allocation of resources) and eight job (activities). The results show that the presented approach is an efficient and easy to implement and can extend to other related problems.

1 INTRODUCTION

Multi-Criteria Decision Making (MCDM) is an extensive field dedicated to selecting the best alternative based on multiple criteria. The application of LP and WGP in MCAP enables decision-makers to account for the relative importance of different criteria, thus leading to more informed and balanced decisions in complex scenarios. More details about Linear programming LP and WGP we refer to [1]-[3].

Yazdani et al. (2019) [4] discuss the necessity of determining criteria weights in MCDM techniques, asserting that the effectiveness of WGP relies heavily on how well these weights are assigned [5]. This emphasis on criteria weights indicates that WGP is adaptable to various contexts, enhancing its relevance in solving MCAPs. Moreover, the study addresses the influence of both subjective and objective weighting methods, suggesting that WGP can accommodate different decision-making preferences [6].

The flexibility of WGP to incorporate subjective and objective weighting methods is particularly beneficial in real-world applications where decision-makers often prefer straightforward approaches. This ease of computation for subjective methods signifies practical implications for WGP, allowing for a more efficient assignment process [7].

The balanced allocation problem, a traditional allocation problem, has received considerable research attention. Several studies suggest that alternative methods exist for solving this problem besides the single stage methods. Meanwhile,

Haleemah et al. (2021) [8] introduced a penalty method to handle the assignment problem with a maximization objective function. The outcomes of the solution matched the results of the Hungarian method's optimal solution. Sadiq et al. (2022) [9] investigated the assignment problem using three techniques: the Hungarian method, the alternative technique, and the new technique proposed by Haleemah et al. Taufik et al. (2023) [10] utilized integer linear programming and the Hungarian technique using Production and Operations Management Quantitative Methods (POM QM) software to solve assignment problems. Vásconez et al. (2024) [11] proposed a smart delivery system to optimize the task assignment problem for delivery personnel with pending orders. The unbalanced assignment problem occurs when the number of activities is not equal to the number of resources, requiring modifications to the single stage method, such as assigning multiple activities to resources or using alternative methods.

Jain et al. (2020) [12] developed an unbalanced time minimization assignment problem using a priority system for projects completed in two stages, with some primary jobs completed in the first stage and the remaining jobs starting after. Anandhi and Geetha (2020) [13] introduced the "Maximum Average with Minimum Cost Method (MAMCM)" for solving assignment problems, which offers the best solution with minimal computation, tested on balanced and unbalanced assignments. However, Wulan et al. (2020) [14] utilized the Kotwal Dhope Method to reduce unbalanced assignments in online higher education courses, with assistance from Hungarian and Matrix One. The study found the proposed method the most cost effective option. Although the authors Rabbani et al. (2020) [15] used a modified Hungarian method with included time parameters to manage job distribution to machines, a numerical example was used. In (2021), Rezaul [16] employed an approach written in Python combined with the Hungarian method to solve balanced and unbalanced assignment problems, achieving similar outcomes to the Hungarian method.

The research above related to the single criteria assignment problem, while the most problem today use multi- criteria in solving assignment problem.

Sheela (2022) [17] introduced a deviation assignment method for solving multi objective problems, comparing it with the Hungarian method and confirming its optimality through numerical examples.

Liu and Yong (2022) [18] used the multi objective decision making mathematical model to optimize performance appraisal in unbalancing human resource allocation. It consists of two objectives: the maximum quality and the minimum time to complete the task. The superior leader determined the objectives' weights, and the problem was solved using the Hungarian method. Tran and Nguyen (2023) [19] investigated and solved two cases of the assignment problem, balanced and unbalanced, solved by the Hungarian method. In the first case, the wage costs were distributed among five employees for five tasks. In the second case, four employees carried out five tasks with three objectives, high quality, and short completion time with the lowest risk (weighting by managers).

While extensive research exists on single-criterion assignment problems including balanced, unbalanced, and time-minimization variants the growing complexity of real-world decision-making necessitates multi-criteria approaches. Recent studies have begun addressing Multi-Criteria Assignment Problems (MCAP), yet many rely on multi-stage processes or require simplification into a single-criterion model, especially under uncertain environments such as neutrosophic conditions. For instance, methods combining Hungarian with weighting or deviation-based approaches still involve sequential optimization steps, increasing computational time and potential information loss. This reveals a clear scientific gap: the absence of an efficient single-stage method capable of directly solving neutrosophic MCAP without criterion conversion. To address this, we propose the RF-WGP approach, which integrates ranking functions and weighted goal programming in a unified framework, enabling direct, time-efficient, and accurate solutions for neutrosophic multi-criteria assignments. The most important drawback for the solution in the proposed methodology in reference [20] in multiple stages and its need to converted a multi-criteria assignment problem into a single- criteria assignment problem.

2 PRELIMINARIES

In this section, some basic concepts for neutrosophic set and numbers are presented. These concepts are taken from [21]-[26].

2.1 Basic Definitions

Definition 1 [21]: Let E be a universe. A single valued neutrosophic set A over E, which can be used in real scientific and engineering applications, is an

neutrosophic set, where the truth-membership function, indeterminacy-membership function and falsity- membership function are respectively is defined by: $T_A: E \to [0,1]$, $I_A: E \to [0,1], and\ F_A: E \to [0,1]$, such that $0 \le T_A + I_A + F_A \le 3$.

Defintion 2 [21]: The trapezoidal neutrosophic nuber A is a neutrosophic set in R with the following truth, indeterminacy and falsity membership functions:

$$T_A(x) = \begin{cases} \frac{a_A(x-a_1)}{a_2-a_1}: a_1 \le x \le a_2 \\ a_A : a_2 \le x \le a_3 \\ a_A\left(\frac{x-a_3}{a_A-a_3}\right): a_3 \le x \le a_4 \\ 0 \quad otherwise. \end{cases} \qquad I_A(x)$$

$$= \begin{cases} \frac{\left(a_2 - x + \theta_A(x-\acute{a}_1)\right)}{a_2-a_1}: \acute{a}_1 \le x \le a_2 \\ \theta_A : a_2 \le x \le a_3 \\ \frac{\left(x - a_3 + \theta_A(\acute{a}_4 - x)\right)}{a_4-a_3}: a_3 \le x \le \acute{a}_4 \\ 1 \quad otherwise. \end{cases}$$

$$\mathrm{F}_A(x) = \begin{cases} \frac{\left(a_2 - x + \beta_A(x-\acute{a}_1)\right)}{a_2-a_1}: \acute{a}_1 \le x \le a_2 \\ \beta_A : a_2 \le x \le a_3 \\ \frac{\left(x - a_3 + \beta_A(\acute{a}_4 - x)\right)}{a_4-a_3}: a_3 \le x \le \acute{a}_4 \\ 1 \quad otherwise. \end{cases}$$

2.2 Ranking Functions

Ranking function is important tool that used to transform fuzzy number or neutrosophic number into crisp number so that an efficient method can be applied easily [27], [28] present new and efficient ranking function as follows.

$$R(\tilde{a}) = \left|\left[\frac{(a^l + a^u) - 3(a^{m_1} + a^{m_2})}{-4}\right] * (T_{\tilde{a}} - I_{\tilde{a}} - F_{\tilde{a}})\right| \quad (1)$$

Where, $\tilde{a} = \{a^l, a^{m_1}, a^{m_2}, a^u\}$ is a trapezoidal neutrosophic number and $(T_{\tilde{a}}, I_{\tilde{a}}, F_{\tilde{a}})$ are the truth, indeterminacy and falsity degrees of this number.

The choice of the presented ranking function is justified as follows: In neutrosophic decision-making problems, objective functions and constraints are commonly expressed in terms of neutrosophic numbers, which involve truth, indeterminacy, and falsity components. However, classical optimization and assignment models require crisp numerical values. Therefore, a ranking function is an essential tool for converting neutrosophic numbers into comparable crisp values.

In this paper, the ranking function proposed in [28] is adopted because it simultaneously considers the truth (T), indeterminacy (I), and falsity (F) degrees of a trapezoidal neutrosophic number. Unlike conventional ranking approaches that rely solely on truth membership, this function explicitly penalizes indeterminacy and falsity, leading to a more balanced and realistic evaluation of uncertain information.

Moreover, the selected ranking function preserves the geometric characteristics of trapezoidal neutrosophic numbers and produces a single representative crisp value without losing essential uncertainty information. This makes it particularly suitable for multi-criteria assignment problems, where consistent comparison among alternatives is required. Its effectiveness and computational simplicity have also been demonstrated in previous neutrosophic optimization studies, which further justifies its selection in the proposed RF-WGP framework.

3 NEUTROSOPHIC ASSIGNMENT PROBLEM

The assignment problem is a special category of transportation problem that deals with assigning tasks to machines and personnel to locations. Assignment problems are often described as applications that are used to assign "activities" to "resources" (or jobs to machines, tasks to employees, etc.) within certain constraints to keep the total cost as low as possible [29].

Also, the assignment problem is one of the fundamental challenges in operations research, since it finds the arrangement that works best [30]. In one –to-many assignment problems

The decision maker is assigning more than one activity to one resource; the resource can achieve more than one activity [31]. The One-to-Many assignment (Called Group Role Assignment) [32]. Some cases of One-to-Many assignment problems such as unbalanced assignment problem which raised when the quantity of resources doesn't match the quantity of tasks [33]. Generalized assignment problem: This problem enables the possibility of assigning multiple activities to a resource while accounting for the amount of the resource's capacity that each activity would require. Each activity in the problem will be assigned to a single resource [34].

More details for assignment problem can found in [35]-[37].

The field of industrial engineering has expanded to include multi-criteria decision-making (MCDM), which focuses on creating mathematical and computational tools to assist decision-makers in their subjective assessment of performance criteria [38], [39].

Three primary techniques are used in MCDM (pairwise comparison, outranking, and distance-based) [40]. The Analytical Hierarchy Process (AHP) and Analytic Network Process (ANP) are techniques for examples pairwise comparison [41], [42].

Examples of outranking techniques include the Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE), which relies on comparison to determine the extent to which one alternative is preferred over another and produces a comprehensive ranking of the alternatives [43], [44].

Through the use of distance-based techniques, the best solution is determined by how close a solution is to the ideal point. Several popular distance-based methods as in [45], [46].

An approach has emerged as a significant method for addressing MCAP by allowing decision-makers to prioritize various criteria through the assignment of weights known as The Weighted Goal Programming (WGP). Recently, netrosophic assignment problem has studied and the objective of this problem is to minimize the total netrosophic cost of assigning all the jobs to the available machines (one machine per job) at the least total cost. For more details we refer to [47]-[51].

4 WEIGHTED GOAL PROGRAMMING (WGP)

Goal programming is a solution method commonly used in practice to convert a multiple objective program into a solvable single objective program. Goal programming requires that the decision maker specifies a goal for each criterion. [52].

The mathematical for preemptive goal programming is given as [52]:

$$Min\tilde{a} = \begin{Bmatrix} P_1[g_1(d_1^+, d_1^-)], P_2[g_2(d_2^+, d_2^-)], . , \\ . P_k[g_k(d_k^+, d_k^-)] \end{Bmatrix} \quad (2)$$

S.t.

$$\sum_{i=1}^{m} C_{in}X_n + d_i^- - d_i^+ = b_i \quad (3)$$

$$\sum_{i=1}^{m} C_{in}X_n \geq, =, \leq b_i \quad (4)$$

$$X_j, d_i^+, d_i^- \geq 0, \;\; n = 1,2,3, \ldots . , N. \quad (5)$$

Where, (4) represent Structural Constraints in goal programming model.

Weighted Goal Programming model consist of multiple objective simultaneously and to assign goals for each objective so that the solution to each goal is achieved. The mathematical model of a WGP is given as [53]:

$$\text{Min}\tilde{a} = \begin{Bmatrix} \text{w}_1[\text{g}_1(\text{d}_1^+, \text{d}_1^-)] + \text{w}_2[\text{g}_2(\text{d}_2^+, \text{d}_2^-)]. . \\ +\text{w}_\text{k}[\text{g}_\text{k}(\text{d}_\text{k}^+, \text{d}_\text{k}^-)] \end{Bmatrix} \quad (6)$$

S.t.

$$\sum_{i=1}^{m} C_{in}X_n + d_i^- - d_i^+ = b_i \quad (7)$$

$$\sum_{i=1}^{m} C_{in}X_n \geq, =, \leq b_i \quad (8)$$

$$X_j, d_i^+, d_i^- \geq 0, \;\; n = 1,2,3, \ldots . , N. \quad (9)$$

Where w_i represent weighted for goal.

In Weighted Goal Programming, the target value g_i epresents the aspiration level associated with the i-th objective and plays a crucial role in guiding the optimization process. In the proposed approach, the target values are determined after transforming the neutrosophic objective functions into crisp forms using the ranking function. Specifically, for each criterion, the corresponding crisp objective function is first evaluated independently under the given system constraints. The optimal or most desirable value obtained from this evaluation is then used as the target value g_i.

This procedure ensures that the targets are realistic, attainable, and consistent with the decision environment. In cases where decision makers have prior preferences or practical benchmarks, these values can also be incorporated as target levels. The deviations from these targets are minimized using weighted penalties, where the assigned weights reflect the relative importance of each goal. This allows the WGP model to handle multiple conflicting objectives simultaneously while maintaining flexibility in prioritization. Thus, the integration of ranking functions with WGP provides a coherent methodological framework: the ranking function handles neutrosophic uncertainty, while WGP manages multiple objectives through well-defined target values and priority weights.

Table 1: Example of Neutrosohpic Data of heavy engineering equipment state company.

Rolling Time			
Job	Machine 1	Machine 2	Machine 3
1	(54,55,56, 57)	(45,46,47,48)	(42,43,44,45)
2	(29,30,31, 32)	(24,25,26,27)	(21,22,23,24)
3	(19,20,21, 22)	(19,20,21,22)	(18,19,20,21)
4	(29,30,31,32)	(27,28,29,30)	(24,25,26,27)
5	(13,14,15,16)	(13,14,15,16)	(12,13,14,15)
6	(37,38,39,40)	(33,34,35,36)	(29,30,31,32)
7	(38,39,40,41)	28,29,30,31)	(24,25,26,27)
8	(17,18,19,20)	15,16,17,18)	(14,15,16,17)
Job	Rolling Cost		
1	(95,96,97,98)	(80,81,82,83)	(44,45,46,47)
2	(28,29,30,31)	(21,22,23,24)	(20,21,22,23)
3	(15,16,17,18)	(16,17,18,19)	(19,20,21,22)
4	(27,28,29,30)	(12,13,14,15)	(21,22,23,24)
5	(11,12,13,14)	(13,14,15,16)	(19,20,21,22)
6	(44,45,46,47)	(35,36,37,38)	(26,27,28,29)
7	(58,59,60,61)	(37,38,39,40)	(27,28,29,30)
8	(14,15,16,17)	(15,16,17,18)	(19,20,21,22)
Job	Rolling Iteration		
1	(11,12,13,14)	(2,3,4,5)	(4,5, 6,7)
2	(4,5,6,7)	(3,4,5,6)	(3,4,5,6)
3	(3,4,5,6)	(3,4,5,6)	(3,4,5,6)
4	(4,5,6,7)	(4,5, 6,7)	(3,4,5,6)
5	(3,4,5,6)	(3,4,5,6)	(3,4,5,6)
6	(5,6,7,8)	(4,5, 6,7)	(3,4,5,6)
7	(7,8,9,10)	(5,6, 7,8)	(4,5, 6,7)
8	(3,4,5,6)	(3,4, 5,6)	(3,4,5,6)

5 EXAMPLE

5.1 Neutrosohpic Data

To show the presented computational approach, we introduce the heavy engineering equipment State company in neutrosophic environment based on the crisp data as in [20] Where, the neutrosophic data consist of three criteria (rolling time, rolling cost, and number of rolling passes), three machines (allocation of resources) and eight job (activities) as shown in Table 1.

The weights of criteria are w_1=0.47, w_2=0.35, w_3=0.18 for rolling time, rolling cost, and number of rolling passes), respectively.

5.2 Implementation of Integrated (RF-WGP) Approach

This approach using to solving a multi-criteria and unbalanced neuromorphic assignment problem that consists of the four main steps as following:

The first step: transform all trapezoidal neutrosohic numbers in Table 1 into crisp numbers using ranking function in (1) with (0.8,0.1,0.1) confirmation degree as in Table 2, Table 3, and Table 4.

The second step: identify the criteria and its weights, where determine the weights of criteria are w_1=0.47, w_2=0.35, w_3=0.18 for rolling time, rolling cost, and number of rolling passes), respectively.

The third step: identify assign matrix that consist of rows present the activities (jobs) and columns represent allocation of resources (machines) as shown in Table 1, then formulate proposal weighted goal programming to find the optimal resource allocation when unbalanced assignment problem m > n, where the number jobs is smaller than the number of machines as following:

$$Min\ Z = \begin{Bmatrix} w_1[g_1(d_1^+, d_1^-)] + w_2[g_2(d_2^+, d_2^-)] \\ +..+w_3[g_k(d_3^+, d_3^-)] \end{Bmatrix} \quad (10)$$

S.t.

$$\sum_{i=1}^{m}\sum_{j=1}^{n} C_{ij}X_{ij} + d_i^- - d_i^+ = g_i\ for\ all\ criteria \quad (11)$$

$$\sum_{j=1}^{3} X_{ij} = 1 \ \ for\ all\ i = 1,2,\dots,m \quad (12)$$

$$\sum_{j=1}^{8} X_{ij} \geq \alpha \ \ for\ all\ j = 1,2,\dots,n \quad (13)$$

$$\sum_{i=1}^{8}\sum_{j=1}^{3} X_{ij} = \beta \quad (14)$$

$$\alpha = \left\lfloor \frac{m}{n} \right\rfloor \quad (15)$$

$$\beta = Max(m,n) \quad (16)$$

$$X_{ij}, d_i^-, d_i^+, \alpha, \beta \geq 0 \quad (17)$$

$$X_{ij} = binary\ variables(0\ or\ 1). \quad (18)$$

Where:

- g_i: represent target for criteria *i*;
- w_i: represent weighted for all criteria;
- X_{ij}:confactor for decision variables;
- C_{ij}:decision variables;
- d_i^-,d_i^+:deviational variables.

Equation (10) shows the assignment problem's objective function, assigning the activities to the resources. Equation (11) represents the criteria constraints that add to it deviation variables. Equation (12) represents the activity(job) constraints where each must be accomplished, therefore equal to one, while (13) shows the resource constraints where each resource must be assigned more than or equal to α, where $\alpha = \left\lfloor \frac{m}{n} \right\rfloor = \left\lfloor \frac{8}{3} \right\rfloor = 2$ as shown in (15). Equation (14) shows that the sum of the activities assigned to the resources that should equal to maximum (total number of activities or total number of resource), where $\beta = Max(m,n) = Max(8,3) = 8$ shown in (15). The (17) shows the non-negative constraint for variables, (18) shows the binary for decision variables.

The fourth step: solve proposal weighted goal programming and find the optimal resource allocation when number of job=8, number of machine=3, number of criteria=3, the right side for goal constraints are 117.6, 124.2, 22.8 respectively represent least sum of time, cost and iterations values for each machine, therefore the mathematical model as following:

$$Min\ Z = 0.47d_1^+ + 0.35d_2^+ + 0.18d_3^+$$

S.t.

$$33.3X_{11} + 27.9X_{12} + 26.1X_{13} + 18.3X_{21} + 15.3X_{22} + 13.5X_{23} + 12.3X_{31} + 12.3X_{32} + 11.7X_{33} + 18.3X_{41} + 17.1X_{42} + 15.3X_{43} + 8.7X_{51} + 8.7X_{52} + 8.1X_{53} + 23.1X_{61} + 20.7X_{62} + 18.3X_{63} + 23.7X_{71} + 17.7X_{72} + 15.3X_{73} + 11.1X_{81} + 9.9X_{82} + 9.3X_{83} + d_1^- - d_1^+ = 117.6$$

$$57.9X_{11} + 48.9X_{12} + 27.3X_{13} + 17.7X_{21} + 13.5X_{22} + 12.9X_{23} + 9.9X_{31} + 10.5X_{32} + 12.3X_{33} + 17.1X_{41} + 8.1X_{42} + 13.5X_{43} + 7.5X_{51} + 8.7X_{52} + 12.3X_{53} + 27.3X_{61} + 21.9X_{62} + 16.5X_{63} + 35.7X_{71} + 23.1X_{72} + 17.1X_{73} + 9.3X_{81} + 9.9X_{82} + 12.3X_{83} + d_2^- - d_2^+ = 124.2$$

$$7.5X_{11} + 2.1X_{12} + 3.3X_{13} + 3.3X_{21} + 2.7X_{22} + 2.7X_{23} + 2.7X_{31} + 2.7X_{32} + 2.7X_{33} + 3.3X_{41} + 3.3X_{42} + 2.7X_{43} + 2.7X_{51} + 2.7X_{52} + 2.7X_{53} + 3.9X_{61} + 3.3X_{62} + 2.7X_{63} + 5.1X_{71} + 3.9X_{72} + 3.3X_{73} + 2.7X_{81} + 2.7X_{82} + 2.7X_{83} + d_3^- - d_3^+ = 22.8$$

$$X_{11} + X_{12} + X_{13} = 1$$
$$X_{21} + X_{22} + X_{23} = 1$$
$$X_{31} + X_{32} + X_{33} = 1$$
$$X_{41} + X_{42} + X_{43} = 1$$
$$X_{51} + X_{52} + X_{53} = 1$$
$$X_{61} + X_{62} + X_{63} = 1$$
$$X_{71} + X_{72} + X_{73} = 1$$
$$X_{81} + X_{82} + X_{83} = 1$$

$$X_{11} + X_{21} + X_{31} + X_{41} + X_{51} + X_{61} + X_{71} + X_{81} \geq 2$$
$$X_{12} + X_{22} + X_{32} + X_{42} + X_{52} + X_{62} + X_{72} + X_{82} \geq 2$$
$$X_{13} + X_{23} + X_{33} + X_{43} + X_{53} + X_{63} + X_{73} + X_{83} \geq 2$$

$$X_{11} + X_{12} + X_{13} + X_{21} + X_{22} + X_{23} + X_{31} + X_{32} + X_{33} + X_{41} + X_{42} + X_{43} + X_{51} + X_{52} + X_{53} + X_{61} + X_{62} + X_{63} + X_{71} + X_{72} + X_{73} + X_{81} + X_{82} + X_{83} = 8$$

$$X_{ij} = binary\ variables(0\ or\ 1)$$

Solving the above model where the result as following:

$$X_{13} = X_{22} = X_{31} = X_{43} = X_{51} = X_{63} = X_{73} = X_{82} = 1$$
$$d_1^- = 0,\ d_1^+ = 3.6, d_2^- = 9, d_2^+ = 0, d_3^- = 0, d_3^+ = 0,$$
$$Z = 0.47(\ d_1^+ = 3.6) + 0.35(d_2^+ = 0) + 0.20\ (d_3^+ = 0) = 1.692$$

Table 2: Crisp values of rolling time.

Job	Machine 1	Machine 2	Machine 3
1	33.3	27.9	26.1
2	18.3	15.3	13.5
3	12.3	12.3	11.7
4	18.3	17.1	15.3
5	8.7	8.7	8.1
6	23.1	20.7	18.3
7	23.7	17.7	15.3
8	11.1	9.9	9.3

Table 3: Crisp values of rolling cost.

Job	Machine 1	Machine 2	Machine 3
1	57.9	48.9	27.3
2	17.7	13.5	12.9
3	9.9	10.5	12.3
4	17.1	8.1	13.5
5	7.5	8.7	12.3
6	27.3	21.9	16.5
7	35.7	23.1	17.1
8	9.3	9.9	12.3

Table 4: Crisp values of rolling iteration.

Job	Machine 1	Machine 2	Machine 3
1	7.5	2.1	3.3
2	3.3	2.7	2.7
3	2.7	2.7	2.7
4	3.3	3.3	2.7
5	2.7	2.7	2.7
6	3.9	3.3	2.7
7	5.1	3.9	3.3
8	2.7	2.7	2.7

5.3 Results and Discussion

To ensure transparency and reproducibility, the comparison with the method in [20] is conducted using the same original problem data, identical job–machine configurations, and the same evaluation criteria (assignment time, assignment cost, and assignment iteration). This guarantees that any observed differences in results are due solely to methodological differences rather than data inconsistencies.

First, the proposed RF-WGP model is applied using trapezoidal neutrosophic numbers, and the resulting assignments and aggregated performance measures are reported in Table 5. Subsequently, for a fair comparison with [20], the same assignments are evaluated using the original crisp data, following the solution structure reported in Table 2 of reference [20]. These results are summarized in Table 6. Finally, Table 7 presents a direct side-by-side comparison between the proposed model and the method from [8].

This step-by-step comparison framework ensures that the results are reproducible and that the evaluation criteria are consistently applied across both methods.

The result shown the jobs (3 and 5) assign on machine1, jobs (2 and 5) assign on machine2 and, jobs (1,4,6 and 7) assign on machine3, can be summary assignment results as following Table 5 depend on trapezoidal neutrosophic number.

The comparison between the result for proposal model and the result reference [20], needs original data depend on the solution in Table 2 as following in Table 6.

Table 5: Summary the result for proposal model depends on trapezoidal neutrosophic number.

Machines	Jobs	Assignment Time	Assignment Cost	Assignment Iteration
Machine 1	Job3, Job5	12.3+8.7=21	9.9+7.5=17.4	2.7+2.7=5.4
Machine 2	Job2, Job8	15.3+9.9=25.2	13.5+9.9=23.4	2.7+2.7=5.4
Machine 3	Job1, Job4 Job6, Job7	26.1+15.3+18.3+15.3=75	27.3+13.5+16.5+17.1=74.4	3.3+2.7+2.7+3.3=12
Total for all criteria		117.6	124.2	22.8
Target criteria		121.2	115.2	22.8
deviational variables		+3.6	-9	0

Table 6: Summary of the result for proposal model depend on original data.

Machines	Jobs	Assignment Time	Assignment Cost	Assignment Iteration
Machine 1	Job3, Job5	20+14=34	16+12=28	4+4=8
Machine 2	Job2, Job8	25+16=41	22+16=38	4+4=8
Machine 3	Job1, Job4 Job6, Job7	43+25+30 +25=123	45+22+27 +28=122	5+4+4+5= 18
Total for all criteria		117.6	198	188
Target criteria		121.2	192	205
deviational variables		+3.6	+6	-7

The key methodological difference between the proposed approach and the method in [20] lies in the solution structure. The method in [20] follows a multi-stage process, where neutrosophic data handling, defuzzification, and optimization are treated as separate sequential steps. This separation can increase computational effort and may propagate approximation errors from one stage to the next. In contrast, the proposed RF-WGP approach operates as a single-stage integrated framework, where: Neutrosophic uncertainty is handled directly through an appropriate ranking function, and Multiple conflicting objectives are simultaneously optimized using Weighted Goal Programming.This integration allows all criteria to be considered concurrently within a unified optimization model, reducing intermediate transformations and improving computational efficiency.

Table 7: Comparison between the result for the proposal model and the result from reference [20].

The model	Total Assignment Time	Total Assignment Cost	Total Assignment Iteration
Proposal model	198	188	34
Reference [20]	207	188	36
The different between two model	9	0	2

The results shown that our proposal model is best from the result reference [20], as following Table 7. As shown in Table 7, the proposed model achieves:

A lower total assignment time compared to reference [8], The same total assignment cost, and A reduction in total assignment iterations.

These results indicate that the proposed single-stage RF-WGP method provides at least equal, and in some cases superior, performance compared to the multi-stage approach in [20]. The reduction in assignment time and iterations highlights the practical advantage of solving the problem in a single integrated stage, especially for large-scale or time-sensitive applications.

6 CONCLUSIONS

The integration of the ranking function and the weighted goal programming approach within the multi-criteria neutrosophic assignment problem framework provides a robust methodology for enhancing decision-making processes under uncertainty and indeterminacy. Also, helps the decision maker to handle the imprecise and inconstant data which are common in real world applications.

The proposed approach was tested using an example of three-criteria neutrosophic assignment problem which represents a neutrosophic extension of the data set presented in [20].

The results showed that the proposed method is more effective in reducing total assignment time and total assignment cost compared to existing approaches.

It also the neutrosophic assignment problems are solved in single stage and do not require converting the multi-criteria assignment problem into a single-criteria assignment problem. This work opens new direction for future studies which can help the decision maker to reach the optimal decision. Further work may focus on extend this research using new ranking functions, and other related real-life applications such as project scheduling, resources allocation, and supply chain management.

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Digital Platforms and Data-Driven Models for Supporting the Transition to Green Energy as a Driver of Sustainable Economic Growth

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Abstract: This study is devoted to the scientific analysis of the transition to green energy and sustainable economic growth at both regional and global levels. The paper examines modern trends in targeted economic investments in the field of renewable energy sources, analyzing the dynamics of national economic growth under modernization processes and the increase in gross domestic product indicators, as well as their impact on environmental sustainability and the improvement of population living standards. The authors employed methods of correlation analysis, multivariate regression, and time series modeling to identify the key factors that shape a synergistic effect. In particular, the findings show that an increase in investments in renewable energy sources by 1 billion USD contributes to GDP growth of approximately 0.05–0.07%, while the expansion of green technologies in the energy sector leads to a significant reduction in greenhouse gas emissions and overall environmental improvement. The analysis further reveals that regional differences are determined by the level of infrastructural development, as well as state and private sector support, which ensures technological progress in the process of transitioning to green energy. The study emphasizes that effective government support and successful international cooperation are crucial factors for the large-scale adoption of green technologies and the achievement of sustainable development goals. The conclusions highlight the necessity of a comprehensive approach, based on in-depth scientific research, to the formulation of national strategies that stimulate investment, foster innovation, and ensure environmental security. The research makes an independent contribution to the development of theory and practice in ecologically oriented sustainable economic development in developing countries.

1 INTRODUCTION

In the era of globalization, the transition of national economies to sustainable, renewable energy sources has become an important aspect of applied scientific research. The depletion and decline of fossil resources, alongside the sharp increase in environmental pollution in various regions of the world, are closely linked with climate change processes. In this context, the shift to green energy acquires strategic importance for ensuring the long-term stability and development of the global economy [1]. It should be emphasized that there exists an inseparable relationship between environmental sustainability and the economic growth of national economies, making the problem of deeply integrating green technologies into national and global strategies particularly relevant [2].

Scientific research in the fields of ecology and sustainable economic development demonstrates that the transition to green energy reduces greenhouse gas emissions, stimulates innovation, and attracts foreign investments in the agricultural sector, industry, and construction of next-generation enterprises. Broad inflows of foreign investment into a country contribute to the creation of new jobs and the stable development of new economic sectors, including the establishment of joint ventures in developing countries [3]. At the same time, numerous debates exist on how the green transition affects the economic growth indicators of national economies, particularly within the framework of national strategies and modernization levels of developing countries.

The methodological foundation of this research is based on the concepts of synergetics, environmental security, stability, and sustainable economic development. The synergetic approach assumes that the close interconnection between the transition to green energy and sustainable economic growth generates an effect greater than the sum of their individual impacts [4]. Within this scientific paradigm, the development and integration of socio-economic structures of green technologies are considered drivers of innovative growth, capable of harmonizing environmental regulation and achieving economic objectives.

Sustainable economic development aims to meet the needs of the population without compromising the ability of future generations [5], [6]. In the context of ensuring energy stability, the integration of ecological, economic, and social aspects becomes increasingly important, requiring a comprehensive analysis of global trends and national strategies.

The connection between the development of renewable energy and sustainable economic growth has become a major subject of global research in recent decades. A plethora of research insists on the importance of green technologies as crucial in national energy systems for economic diversification, industrial modernization, and long-term environmental sustainability. For example, based on [3] renewable energy investment are them important driver of productivity improvement and leading to new high-technology sectors growth; while [7] stress the heterogeneity in these effects among emerging economies. This overall trend is supported by the global literature, which demonstrates that the shift towards green energy brings about direct and indirect positive impacts in terms of higher levels of employment, better security of supply when it comes to energy sources, and lower production costs in the long term.

1.1 Literature Review

International academic literature has paid great attention to the pattern of correlation between green energy transition and sustainable economic growth. Current literature highlights that renewable energies development creates a multidimensional impact on economic, environmental and social subsystems. So also, the move to Renewable Energy and Investments was identified by [3] as a longterm economic benefit achieved through stimulation of investments in new industries, improvement on technological innovations and increased in productivity. Their worldwide analysis showed that economies powering up with green energy grow faster than those relying on dirty energy.

For developing countries, a relevant but varying relation between RE growth and GDP increases was observed for emerging economies by [7]. They contend that the extent of economic impact is largely dependent on structural factors – infrastructure preparedness, quality of governance and access to international finance. Liu et al. [8] also emphasize that renewable energy development is stimulated in BRICS countries based on the rationale of ensuring energy security, environmental quality and industrial diversification, while some institutional and financial barriers restrict their potential.

Many studies emphasize the technological and environmental dimensions of the green energy transition. For instance, Amari et al. [9] demonstrate that advanced photocatalytic materials can significantly improve the efficiency of hydrogen production while simultaneously contributing to environmental purification processes. These findings highlight the potential of innovative materials in supporting low-carbon energy systems.

In addition, recent works focus on the development and optimization of renewable energy systems. Zikrillayev et al. [10] investigate the modeling of autonomous solar power systems, showing their applicability for decentralized energy supply. Similarly, Yuldoshov et al. [11] analyze the influence of temperature on photovoltaic module performance, emphasizing the importance of environmental conditions for system efficiency. Furthermore, Saitov et al. [12] propose methodologies for the calculation and optimization of solar energy conversion, contributing to improved design and operation of photovoltaic systems.

At the same time, the literature indicates several technical and implementation challenges. The performance of renewable energy technologies depends on environmental factors, system configuration, and efficiency of energy conversion processes. These limitations highlight the need for further research in system optimization, modeling, and integration of renewable energy technologies into practical applications. On the whole, there is compelling evidence in the scientific literature that renewable energy expansion can make a critical contribution to sustainable development and create synergetic effects for governments via integrated policies, good governance and continuing technological improvement. This work develops the existing literature and advances it by performing a global comparative analysis complemented with regression models in order to bring out key drivers of the economic impact of the green transition.

1.2 Research Gap and Objectives

In the process of modernizing the national economies of developing countries, there has been a significant increase in foreign investments in renewable energy. Global investments in renewable energy reached a record of 500 billion USD in 2022, which is 20% higher compared to the previous year [6], (Fig. 6). The main drivers of this growth are the decreasing costs of solar and wind technologies and the growing influence of international climate agreements (Table 1).

Despite the plethora of studies analyzing the economic and environmental consequences of the green transition, most existing research is limited to individual regions or specific technological options. There is still relatively little cross-country comparison work that systematically combines these investment dynamics, renewable energy penetration, economic growth signals, and environmental outcomes. Furthermore, several existing studies are based on limited-scope datasets or only short-term observations, which might not be long enough to capture long-term synergetic effects. Thus, the lack of a complete global study, including statistical modelling, correlation analysis, and comparative evaluation, is a significant research gap. This study aims to fill this void by providing a comprehensive empirical analysis of large economies and emerging market regions.

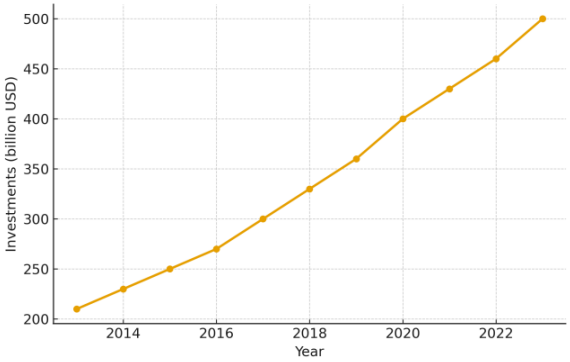


Figure 1: Global investments in renewable energy sources (2013–2023) [6].

Table 1: Main indicators of green technology development by country (2022) [6].

Country	Investment Volume (billion USD)	Share of Renewables in Energy Balance (%)	Number of New Renewable Projects
China	120	45	1500
USA	90	25	800
Germany	70	35	950
India	50	20	1200
Brazil	30	40	600

Comprehensive scientific studies confirm that the implementation of green technologies can have both stimulating and constraining effects on the economic growth of national economies. On the one hand, green energy fosters the creation of new markets, enhances energy efficiency, and reduces costs, which leads to GDP growth [7]. On the other hand, initial investments and structural transformations in the energy sector may result in temporary bottlenecks and slowdowns in growth.

Currently, different perspectives are presented in scientific literature. Research indicates [8], [9] that in countries with a high level of green technology development, there is a positive correlation between the green transition and GDP growth. At the same time, in developing countries with weak infrastructure and limited capital, the effect may be less pronounced or even negative [10], (Fig. 2).

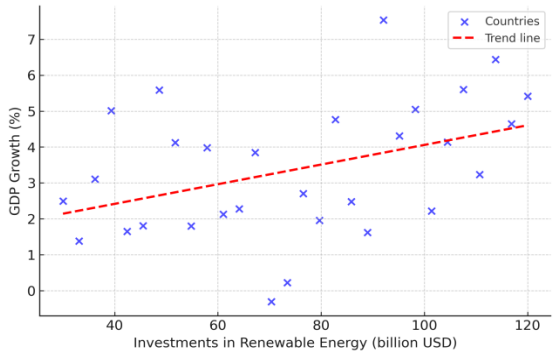


Figure 2: Correlation between investments in green energy and GDP growth across countries [7].

Such findings are consistent with theoretical postulations emanating from synergetics and sustainable development, which propose that interacting economic and environmental systems can produce the emergence of effects that are greater than their individual parts. As demonstrated by Liu et al. [8] From the preceding analysis, bringing in green technology will increase system stability and lower ecological risk and social economic restructuring. These findings provide the theoretical underpinning of the present paper, which argues that economic transformation toward renewable energy should be conceptualized not only as an eco-technological change but also – and foremost – as integral long-term development towards sustainability.

Despite positive trends, the transition to green energy faces several challenges. Foremost among them are the need for large-scale investments, systematic infrastructure upgrades, energy storage solutions, and integration of renewable sources into existing energy systems [11]. In addition, geopolitical issues related to conflicting economic interests and the use of natural resources in developing countries remain important.

Social aspects must also be considered, such as the potential emergence of energy inequality, the level of professional training of engineering personnel, and public perception of new technologies.

Future prospects are closely associated with the adoption of innovative technologies, digitalization of the energy complex, and closer international cooperation. Within the framework of the United Nations Sustainable Development Goals (SDG 7 and SDG 13), the transition to green energy is regarded as a strategic tool for achieving global targets [12].

The main objective of this study is to identify and analyze the synergetic mechanisms of interaction between the transition to green energy and sustainable economic growth at the global level. The following tasks are set within the framework of the research:

- Analyze key trends and dynamics in the growth of green technologies.
- Determine the impact of the green transition on sustainable economic development indicators.
- Compare the experiences of leading developed countries and identify the most effective strategies.
- Develop recommendations for optimizing the interaction between environmental security and sustainable economic stability.

To achieve these objectives, methods of comparative analysis, statistical modeling, and a systems approach were employed. Sources included reports and databases of international organizations, scientific articles, monographs, and analytical materials published in leading academic journals.

This research is relevant in the context of global efforts to ensure environmental security and economic sustainability. The study demonstrates that the transition to green energy is not only a factor of environmental protection but also a significant driver of economic development, possessing substantial potential for synergetic interaction. The authors conducted an in-depth empirical analysis as well as a comparative study of national strategies and their impacts on economic growth.

2 MATERIALS AND METHODS

2.1 General Provisions

This study is based on a comprehensive approach that combines qualitative and quantitative analyses, comparative analysis, and modeling. The main objective is to identify and systematize the mechanisms of interaction between the transition to green energy and economic growth at the global level. For this purpose, modern statistical methods, data analysis, regression modeling, and visualization of results in the form of tables and graphs were employed.

The object of the study is the indicators of green technology development and the dynamics of economic growth in leading countries over the past 15 years (2008–2023). The sources of data include international organizations (International Energy Agency, World Bank, United Nations), national

reports, scientific publications, analytical reviews, and statistical yearbooks [13].

2.2 Data Sources and Their Characteristics

The following main data sources were used for the analysis:

- International Energy Agency – data on global investments in renewable energy sources, volumes of renewable energy production, and the level of penetration of green technologies in the energy sector [1].
- World Bank – macroeconomic indicators, gross domestic product, development indexes, and investment statistics [5].
- United Nations – reports on Sustainable Development Goals, indicators of environmental safety and social development [2].
- National statistical services – country-specific data (China, USA, Germany, India, Brazil, etc.).

To ensure representativeness and statistical reliability, aggregated data by countries and regions, as well as dynamic time series by years, were used.

2.3 Methods of Statistical Analysis

2.3.1 Descriptive Statistics

At the initial stage, descriptive statistics were conducted on key indicators – investments in green energy, gross domestic product, the share of renewable sources in the energy balance, and the number of new projects (see Table 2). This made it possible to determine major trends, detect outliers and anomalies, and prepare the data for further modeling.

Table 2 Summary statistics of core macro-energy indicators for 2022 Descriptive Statistics for Core Macro-Energy Indicators_1 shows the descriptive statistics of the core tableau depicting LCOE, renewable capacity factor, and energy demand in the examined countries in 2030. LSM as land suitability maps. That on renewable energy (AVERAGE, = USD 75 billion) recurrently varies considerably (SD = 30), indicative of uneven financial commitment across the state. The contribution of renewables to the national energy balance varies between 20% and 45%, with an average share value of 32%, that is, demonstrating a moderate increase in the integration of alternative energy sources. GDP growth demonstrates relatively constant performance (mean = 3.2%), although the variability (0.5%–6.7%) suggests differences in economic adaptability. However, the number of new renewable energy projects that are newly developed is particularly varied, with a mean of 950 projects per year (SD = 400) and ranging from 600 to 1,500 in different areas, indicating the diverse institutional capacity and investment environment within the regions.

Figure 3 presents the geographical distribution of investment in renewable energy in 2022, which shows marked differences between world regions. The largest proportion of that is in Asia, where $180 billion has already been spent on deploying solar, wind, and hydrogen technologies at a rapid pace. Europe comes in second with USD 120 billion, largely due to significant policy inducements resulting from the EU's Green Deal. America tracks USD 100 billion, showing slow but relatively sluggish growth, and Africa has the smallest level of investment at USD 40 billion, with continued financial and infrastructural challenges. The visual comparison highlights that the distribution of financial support for renewable energy is not evenly spread across the globe and suggests a case for targeted incentives in under-supported areas.

Table 2: Descriptive statistics of key indicators (2022) [1].

Indicator	Mean Value	Standard Deviation	Minimum	Maximum
Investments in renewable energy (billion USD)	75	30	30	120
Share of renewables in energy balance (%)	32	8	20	45
GDP growth (%)	3.2	1.4	0.5	6.7
Number of new renewable projects	950	400	600	1500

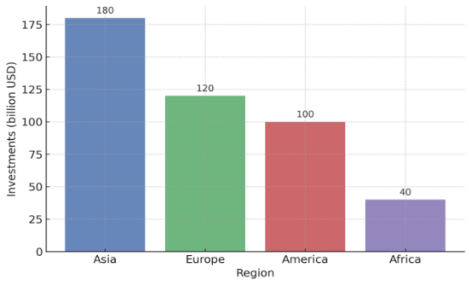


Figure 3: Distribution of renewable energy investments by regions in 2022 [1].

2.3.2 Correlation Analysis

To determine the relationships between variables, Pearson's correlation coefficient was applied. In particular, the relationships between investments in green energy and GDP growth, the level of renewable energy penetration, and development indexes were analyzed.

Table 3: Correlation coefficients between key variables [2].

Variables	Correlation Coefficient
Investments in renewables and GDP growth	0.75
Share of renewables and environmental efficiency index	0.68
Number of projects and investments	0.83

Table 3 Correlation coefficients of key variables in the renewable energy sector There are strong and statistically significant associations among the key variables. Renewable energy investments show a strong positive correlation with GDP growth (0.75), indicating that greater financial commitment to clean energy is significantly related to a higher level of economic performance. The contribution of renewables to the energy mix is also significantly positively correlated with the environmental efficiency index (r = 0.68), suggesting that increasing renewable penetration results in improved ecosystem outcomes. The highest association is with the number of renewable energy projects and total investment (r = 0.83), indicating that the amount of capital available dictates how much project deployment will increase.

2.3.3 Multiple Regression Analysis

To quantitatively assess the influence of factors on GDP growth, a multiple regression model was constructed of the following form:

$$GDP\ Growth_i = \beta_0 + \beta_1 \times Investments_i + \beta_2 \times Share\ of\ renewables_i + \beta_3 \times Number\ of\ projects_i + \varepsilon_i,$$

where i represents a country or region.

The model was estimated using the least squares method, with verification of the statistical significance of coefficients and residual analysis. Evaluation criteria included R-squared, F-test, and p-values.

2.3.4 Time Series Analysis and Trend Modeling

To study the dynamics of green technology development, time series analysis was applied. Trend and seasonality models were built using exponential smoothing and ARIMA models [13].

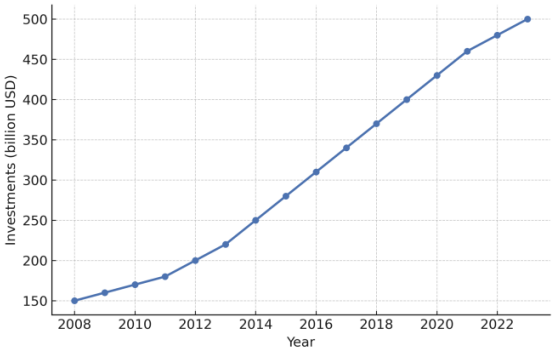


Figure 4: Trend of renewable energy investments (2008–2023).

As shown in Figure 4, global investments in renewables followed a consistent upward path during this period. Global investment increased from a little under USD 150 billion in 2008 to almost USD 500 billion by 2023, with rapid growth in solar, wind, and other green technologies. Arguably, the most notable acceleration took place post-2014 when climate policies were reinforced, technology costs fell further, and the private sector became more involved. The continued increase in investment levels demonstrates increasing global dedication to the clean energy transition and expansion of renewable infrastructure around the world.

2.4 Data Visualization and Modeling

A scatter plot (see Fig. 1) demonstrated a strong positive correlation, confirming the hypothesis of a synergetic effect.

A sensitivity analysis of the regression model to input parameter variations was conducted.

Table 4: Sensitivity analysis of the regression model.

Input Factor	Impact on Model (%)	p-value
Investments in renewables	45	<0.01
Share of renewables	30	0.02
Number of projects	25	0.05

Table 4 Sensitivity analysis for the regression model: relative importance of selected key input factors in terms of their impact on the model's explanatory power. Investments in renewable energy stand out as the most influential variable, representing 45% of the model's variability, with a significance p-value (<0.01) that suggests strong prediction relevance. The proportion of renewables accounts for 30% and is statistically significant (p = 0.02), suggesting its importance in shaping the total performance results. The percentage of renewable-energy projects constitutes the gap with a marginally significant p-value (0.05), indicating that it is a moderate from 25 percent to still significantly influencing on the other hand. In summary, the sensitivity analysis highlights that investment amounts are the primary determinant of the modelled relationships, while renewable-share and count help to explain some of the residual variance.

2.5 Reliability and Validity Assessment Methodology

To evaluate the reliability and robustness of the models, standard statistical criteria were applied: confidence intervals, variance inflation factor (VIF) tests for multicollinearity, residual analysis, and cross-validation.

The results demonstrated high statistical significance and explanatory power of the model ($R^2 = 0.78$), confirming its adequacy.

2.6 Additional Methods and Tools

The study employed modern software tools such as SPSS, R, Python (pandas, statsmodels, matplotlib), Excel, and Power BI for visualization. Special attention was paid to data validation, detection of outliers and missing values, as well as the standardization of variables to ensure comparability.

This section provides a detailed description of the methods used to analyze the relationship between the transition to green energy and economic growth at the global level. The applied statistical tools and models allowed the identification of significant relationships, the determination of key factors influencing the development dynamics of green technologies, and the evaluation of the effectiveness of various strategies. The following sections of the study will be devoted to interpreting the obtained results, identifying regularities, and formulating recommendations for government institutions and the business community.

3 RESULTS OF THE RESEARCH

This section presents the main empirical findings obtained from the analysis of the relationship between the transition to green energy and economic growth at the global level. Based on statistical models, correlation analysis, regression studies, and time series, key patterns were identified that confirm the existence of synergetic effects in this area.

First, the dynamics of investments in renewable energy, their influence on economic development indicators, and comparative analysis by regions and countries are considered. Particular attention is paid to the identification of factors most significant for stimulating sustainable growth during the green energy transition.

3.1 General Dynamics of Investments in Renewable Energy and Their Impact on Economic Growth

On the global scale, there has been steady growth in investments in renewable energy, confirmed by the data in Table 5. In 2022, global investments in renewable energy reached a record 520 billion USD, 22% more compared to 2021 and three times higher than in 2010 [1].

Table 5: Global investments in renewable energy and penetration levels, 2010–2022 [1].

Year	Investments (billion USD)	Share of Renewables in Energy Balance (%)	Number of New Projects	Total Installed Capacity (GW)
2010	180	20	1200	150
2012	240	23	1400	200
2015	350	28	1800	300
2018	430	30	2200	400
2020	480	32	2500	470
2022	520	35	2800	550

Table 5 presents a longitudinal overview of global renewable energy development from 2010 to 2022, highlighting consistent growth across key indicators, including investment volumes, the share

of renewables in the energy mix, project deployment, and installed capacity. Over this period, investment increased substantially, reflecting the intensification of financial support for the clean energy transition. At the same time, the share of renewable energy expanded, indicating a gradual structural transformation of the global energy system. The number of implemented projects and total installed capacity also grew significantly, confirming the large-scale expansion of renewable energy technologies worldwide. These trends suggest that the development of the sector is driven by a combination of policy support, technological progress, and increasing market demand.

Figure 5 illustrates the dynamics of investments and installed capacity, revealing a clear upward trend and a close relationship between these indicators. The parallel growth of financial inputs and capacity expansion suggests that capital inflows directly contribute to the large-scale deployment of renewable energy technologies. This pattern reflects the increasing maturity of the sector and the strengthening role of renewables in the global energy market.

The results of the multiple regression analysis further confirm the existence of a statistically significant positive relationship between investments in renewable energy and GDP growth across countries and regions (Fig. 6). This finding indicates that increased investment activity in the renewable energy sector is associated with measurable economic effects, supporting the role of green energy as a factor of economic development.

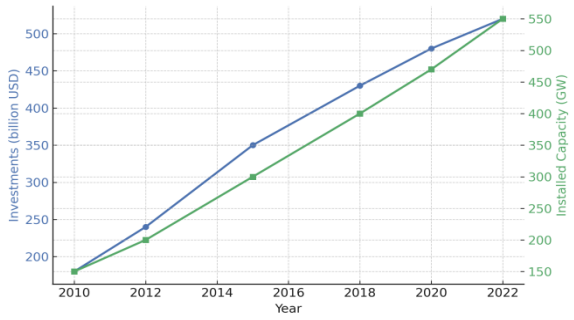


Figure 5: Dynamics of Renewable Energy investments and installed capacity (2010–2022) [1].

The regression results of the effect of investment in renewable energy on GDP growth in different regions are presented in Table 6. The results indicate that Asia demonstrates the largest association with $\beta = 0.065$ and a significantly high p-value (< 0.01) along with a very strong fit ($R^2 = 0.72$), suggesting that investment in renewables is a key driver of economic growth on the continent.

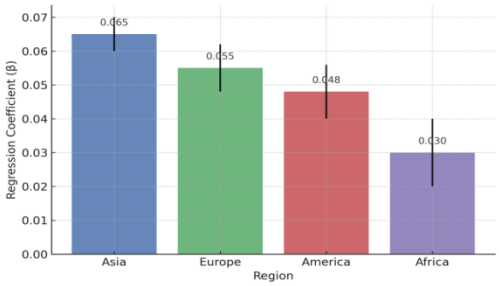


Figure 6: Impact of renewable energy investments on GDP growth by regions (regression analysis, 2022).

Table 6: Regression coefficients of the impact of Renewable Energy investments on GDP by regions [2].

Region	Coefficient β	p-value	R^2 of Model
Asia	0.065	<0.01	0.72
Europe	0.055	<0.05	0.68
America	0.048	<0.05	0.65
Africa	0.030	0.08	0.50

Europe and America demonstrate moderate effects ($\beta \approx 0.055$ and $\beta = 0.048$), which remain statistically significant, with R^2 values ranging from 0.65 to 0.68, indicating a consistent but regionally differentiated economic response. Africa exhibited the lowest correlation ($\beta = 0.030$) with an insignificant p-value of 0.08 and a weaker model fit ($R^2 = 0.50$), suggesting that structural constraints and low investment capability might dampen the economic effect of renewable energy outlay. Overall, the estimation results suggest that investment in renewable energy significantly promotes growth, but its impact differs by regional economic structure and institutional preparedness.

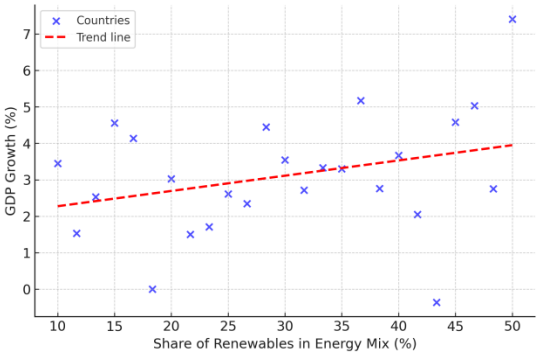


Figure 7: Correlation between the share of renewables in the energy mix and GDP growth by countries (2022).

The analysis revealed that an increase in the share of renewable energy in the overall energy balance contributes to GDP growth, especially in countries with high technological maturity (Fig. 7).

The correlation coefficient of 0.68 confirms the importance of increasing the share of green energy for stimulating economic growth.

3.2 Changes in Environmental Indicators

The analysis showed that increasing investments in renewable energy contributes to reductions in air pollution and greenhouse gas emissions.

Table 7: Environmental indicators and renewable energy investments (2010–2022) .

Year	Invest-ments (billion USD)	CO_2 Emissions (million tons)	Air Pollution Index	Domestic Emissions (%)
2010	180	36,000	78	–
2012	240	33,500	72	-3.4%
2015	350	29,000	65	-4.7%
2018	430	26,500	60	-4.6%
2020	480	24,000	55	-4.4%
2022	520	21,500	50	-4.2%

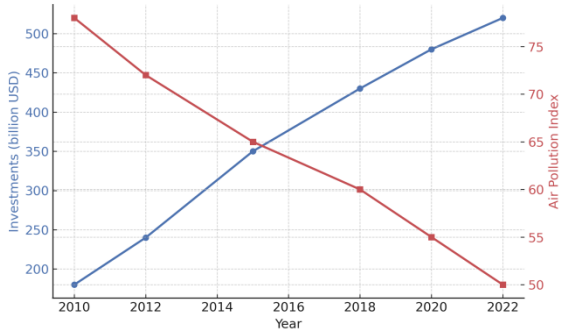


Figure 8: Relationship between investments and air pollution levels (2010–2022).

Table 7 depicts the movements of major environmental indicators with respect to renewable energy investments over the years 2010-2022. Figure 8 provide a very instructive negative correlation: investments in renewable energy have continuously increased from USD 180 billion (2010) to USD 520 billion (2022), while CO_2 emissions have constantly fallen from 36,000 million tons to 21,500 million tons. An Air Pollution Index of 78-50 was observed during the same period, signifying a remarkable improvement in air quality. Furthermore, domestic emissions rates amount to steady negative figures (from –3.4% to –4.7%), which means that national greenhouse gas production decreases gradually. "Overall, it illustrates the positive environmental impact that greater investment in renewable energy could have, and the headway we are making for clean air."

The results indicate a strong inverse relationship: the higher the investment in renewables, the lower the pollution level.

3.3 Impact of Green Technologies on Quality of Life

Sociological and environmental indices demonstrated that an increasing share of renewable energy improves quality of life by reducing morbidity rates and contributing to ecological security.

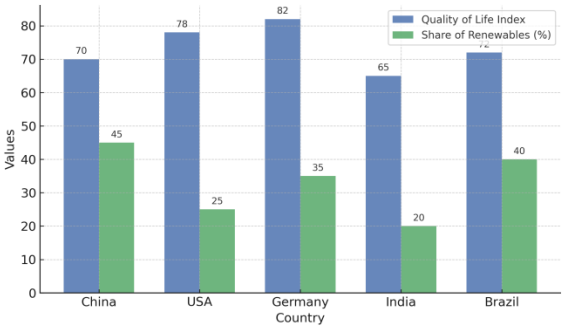


Figure 9: Quality of life index and the share of renewables in the energy mix by countries (2022) [2].

The quality of life index and share of renewables in the national energy mix up to 2022 are provided for five countries in Figure 9. Germany has the highest quality of life score (82) and a very strong renewable energy share (35%), which emphasizes its progressive sustainability laws. The USA and China exhibit similar high quality of life values (78 and 70, respectively) but very different shares of renewables – 25% in the USA versus 45% in China – suggesting differing national energy transition approaches. Brazil: Brazil has a moderate quality of life (75) and a large share of renewables (40%), an indicator of the high significance of hydroelectric power for Brazil for several decades. India comes up at the bottom, with a PpL of 65 and 20% renewables, illustrating how difficult it can be to juggle social and economic development as well as cleaner energy uptake. On the whole, the picture shows a general pattern: "The higher the renewable penetration levels, the better they are doing in terms of environmental and social dimensions," which feeds positively into quality-of-life indicators.

Table 8: Main indicators for leading countries (2022) [1].

Country	Investments (billion USD)	Share of Renewables (%)	Installed Capacity (GW)	GDP Growth (%)
China	120	45	950	4.0
USA	90	25	620	2.3
Germany	70	35	580	1.8

3.4 Regional Specificities and Comparative Analysis

Key indicators for leading countries in the field of green energy are presented in Table 8. China, the USA, and Germany demonstrate the most significant progress in investments and technology deployment.

The main RE and economic indicators are shown in Table 8 for a comparison of the three advanced countries in 2022. China is the best performer on aggregate (the highest renewable energy investment of USD 120 billion, the largest percentage of renewables in its total primary and final energy consumption – with 45%, as well as installed renewable power capacity: 950 GWs) next to sustained GDP growth (4.0%). The US comes next with USD 90 billion, and renewables at 25%, but where installed capacity (620 GW) is high and economic growth is moderate at 2.3%. Germany has a high level of technology development with 35% renewables and 580 GW installed capacity, but lower GDP growth (1.8%), indicating that its economy is mature with slower growth. Overall, the table illustrates how variable the levels of renewable investment, scale of deployment, and economic results are across countries, with China being the global leader in green energy expansion.

India and Brazil demonstrate rapid growth in investments and renewable energy deployment despite less developed infrastructure.

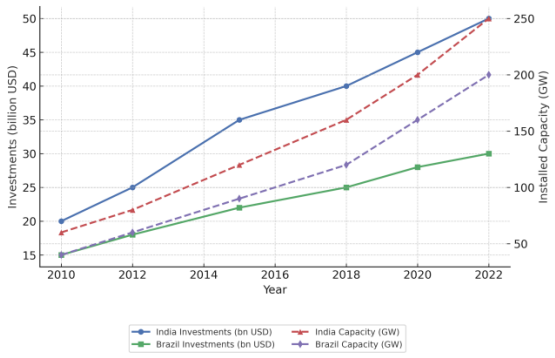


Figure 10: Growth of renewable energy investments and deployment in India and Brazil (2010–2022).

Figure 10 depicts the long-term development of RE investments and capacity in India's RE systems compared to Brazil 's from 2010 to 2022. Both countries exhibit an upward trend, with India performing far better than Brazil in nearly all respects. India's renewable investments grew from 18$ bn in around 2010 to about 50$ bn by 2022, with a consequent increase in installed capacity from 60 GW to 250GW. In Brazil, positive but moderated growth is also evident as capacity increases to 150 GW from 40 GW, and investments double ($15 billion to $30 billion). The relative steepness of the lines distinguishes India's greater efforts at policy commitment, market size, and renewable energy expansion rates. Overall, the figure verifies that the deployment of renewables has accelerated rapidly in both economies and reveals India's superior position regarding investment value and capacity addition.

4 DISCUSSION

This section interprets the results, highlights their significance, and discusses implications for the theory and practice of transitioning to green energy and sustainable development. The analysis confirms a mutually reinforcing relationship between investments in renewable energy and economic growth, revealing the mechanisms of this interaction at the global level. Findings are compared with existing studies, limitations are acknowledged, and directions for further research are proposed.

4.1 Interpretation of Results

The study identifies a strong positive relationship between investments in renewable energy and economic growth (see Fig. 11, Table 6). This indicates that green investments function not only as an environmental instrument but also as a driver of macroeconomic development.

Beyond direct financial returns, renewable energy investments stimulate innovation, enhance energy efficiency, and foster structural improvements in the economy. These outcomes align with previous research [5], which shows that

countries prioritizing green technologies achieve more stable and sustainable economic performance.

The effectiveness of these investments varies across regions. Economies with developed infrastructure, advanced technological capabilities, and supportive regulatory frameworks generally experience higher returns, emphasizing the role of institutional and structural factors in maximizing the benefits of the energy transition.

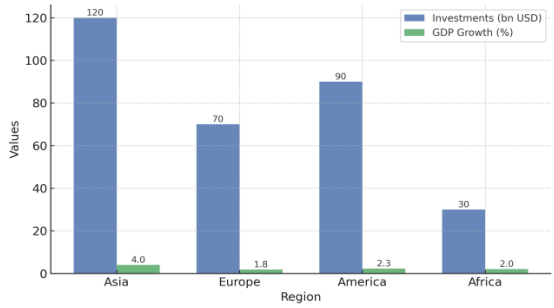


Figure 11: Impact of renewable energy investments on GDP growth by regions (2022) [2].

4.2 Environmental and Economic Implications

Environmental analysis demonstrates that increased investments and higher shares of renewables significantly reduce greenhouse gas emissions (see Fig. 12, Table 7). This supports the contribution of green energy transition to the objectives of the Paris Climate Agreement.

The reduction of CO_2 emissions is closely linked to the growth of renewable energy investments, with the pace of reduction increasing as the share of renewables expands. Technological innovations, improved energy efficiency, and modern energy storage systems drive this effect.

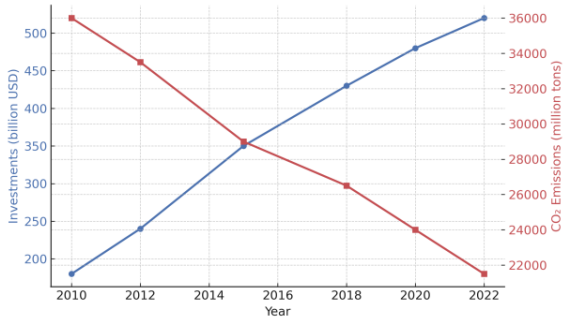


Figure 12: Relationship between investments and CO_2 emissions reduction (2010–2022).

Countries with higher levels of investment achieve greater environmental efficiency, improving quality of life, reducing morbidity, creating jobs, and enhancing ecological conditions.

4.3 Regional Differences

The impact of renewable energy investments varies significantly by region. Asia and Europe show the most pronounced economic and environmental benefits, driven by high investment volumes, developed infrastructure, and supportive institutions (Table 9).

Table 9: Regional differences in the effectiveness of green investments (2022) [1].

Region	Average Investment Activity (billion USD)	Average GDP Growth (%)	Share of Renewables (%)	Pollution Index
Asia	120	4.0	45	50
Europe	70	1.8	35	55
America	90	2.3	25	60
Africa	30	2.0	10	70

In regions with lower investment levels, such as parts of Africa and Latin America, the benefits are less pronounced due to limited technological capabilities, unstable conditions, and insufficient financing. This underlines the importance of tailored regional strategies.

4.4 Limitations

Several limitations were identified. Investments may not yield expected outcomes where infrastructure is weak, regulatory incentives are absent, or technological maturity is insufficient.

In underdeveloped regions, substantial investments may have limited effects on economic growth and environmental sustainability (see Fig. 13), highlighting the need for comprehensive strategies that include infrastructure development, workforce training, and government support.

Social and economic risks, such as potential energy price increases and emerging energy inequalities, also exist. Additionally, the econometric models employed may face constraints like multicollinearity, residual autocorrelation, and other statistical challenges.

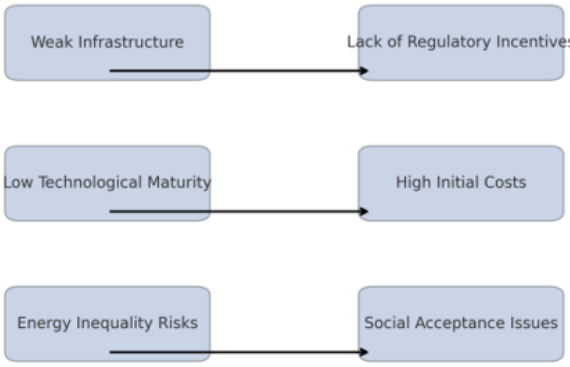


Figure 13: Constraints and barriers to the implementation of green technologies (schematic).

4.5 Policy and Institutional Factors

Government support and regulatory frameworks are critical to investment effectiveness. Favorable legal environments correlate with higher investment efficiency and faster growth in the share of renewables (see Fig. 14).

State programs, subsidies, and tax incentives play a significant role in accelerating the adoption of renewable energy technologies.

Figure 14: Relationship between levels of government support and renewable energy implementation (2022).

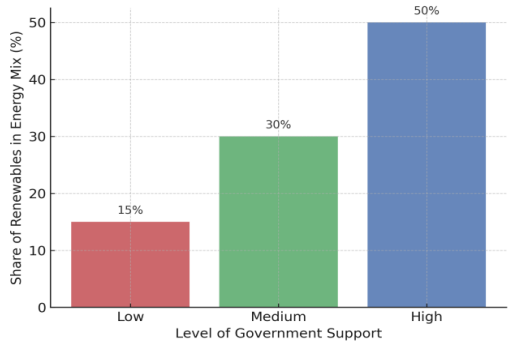


Figure 14: Relationship between levels of government support and the implementation of renewable energy (2022).

5 CONCLUSIONS

The study confirms a positive relationship between renewable energy investments and economic growth globally. Increased financial support for green energy contributes both to environmental sustainability and measurable economic benefits.

Higher investment levels are linked to steady GDP growth and reduced greenhouse gas emissions, demonstrating a mutually reinforcing effect where economic development and environmental improvement occur simultaneously.

Significant regional differences are evident. Advanced technological infrastructure, strong institutions, and active government support enhance outcomes, while limited investment capacity and weaker infrastructure reduce efficiency.

Effectiveness depends on regulatory conditions, technological readiness, and financial availability. Econometric analyses may also face standard statistical limitations.

Overall, the transition to green energy is a key driver of sustainable development, combining economic growth with environmental protection. Continued investment, policy support, and international collaboration are essential for an effective energy transition.

6 FURTHER RESEARCH

Limitations include:

- Limited data availability for some countries
- Potential distortions between investment volumes and economic effects
- Regression models may not capture nonlinear and complex interactions

Future research directions:

- Develop multidimensional models incorporating social, economic, and technological factors
- Analyze long-term prospects of renewable energy transition
- Study the impact of innovative technologies on synergetic processes
- Explore international cooperation and global initiatives

The study highlights the importance of green energy investments for sustainable economic growth and environmental security. Regional differences and limitations require tailored strategies, active policy support, and international collaboration to ensure large-scale adoption of green technologies.

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Digital Tools and Information Systems in National Strategies for Sustainable Green Energy Transition

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Keywords: Green Energy, Renewable Energy Sources, Energy Transition, National Strategies, Investments, Scenario Modeling, Technological Innovation, International Cooperation.

Abstract: This paper analyses national policies for the move towards green energy, considering global tendencies, investment dynamics, and socio-economic policy instruments in place between 2013 and 2024. This study further investigates the main drivers of growing renewable energy generation, investment amount, tariff systems and policies, tax-justice policies, subsidies, technological innovation, and international inter-investment. The study uses statistics from international and national organizations, regression analysis, comparative analysis, and scenario forecasting methods to determine the most effective measures for promoting green energy transition. The findings demonstrate that countries succeed in implementing renewable energy if they combine economic tools, of which the annual investment amounting to over 500 BN USD takes a significant share. Not only does technological advances, especially the decrease in the cost of solar and wind technologies, considerably enhance the competitiveness of renewable systems. In addition, upgraded infrastructure and regulatory mechanisms contribute to long-term sustainability. Analytical tables and charts in the article show investment directions, modeling results, and projection contents for major global areas. The study offers, at best estimation, a theoretical and integrated approach to the literature that combines investment patterns, policy tools, and scenario types into a single analytical frame for evaluating national green policy strategies. By analyzing the systemic connections between financial flows, policy instruments, and renewable energy development, we build on previous research and address methodological blind spots in comparative strategy investigations. In practical terms, these results provide evidence-based advice to governments, policymakers, and investors. The findings could contribute to improving national policies, strengthening tariff and subsidy structures, and better informing public and private investments. These findings can inform how countries can enhance energy security, reduce emissions more quickly, and stay on track with their long-term climate goals. The report argues that the development of international relations and further investment in new technologies are crucial for achieving a secure transition to green energy.

1 INTRODUCTION

In the context of global climate change, freshwater scarcity, the necessity for rational use of natural resources, and persistent air pollution, the transition to sustainable energy has become one of the most urgent priorities. National strategies for the development of green energy play a critical role in this process, encompassing a wide range of economic and environmental measures aimed at reducing dependence on fossil fuels, increasing the share of renewable energy sources (RES) in the energy balance, and creating favorable conditions for

environmentally sound and sustainable economic development. Within the framework of the global agenda – such as the Paris Agreement and the United Nations Sustainable Development Goals (SDGs) – countries are developing and implementing their own strategies for transitioning to green energy, providing a rich foundation for comparative studies and for analyzing the effectiveness of modernization strategies for national economies under conditions of globalization [11].

1.1 Relevance of the Research

Amid globalization, investments in the renewable energy sector have grown significantly, driven both by environmental requirements and by the need to address acute socio-economic challenges in individual countries. According to the International Energy Agency, the share of renewables in the global energy balance reached 29% in 2023, up 4% compared to 2018 [2]. This growth is driven by technological progress, falling costs of renewable technologies, and proactive national and international government initiatives.

However, approaches to implementing green energy strategies vary considerably across countries, influenced by factors such as the level of economic development, institutional and business support, natural resource potential, and international commitments. Consequently, a comparative analysis of the goals, content, and mechanisms of national strategies makes it possible to identify best practices, evaluate key socio-economic instruments, and determine which innovative measures are most effective for accelerating the transition to sustainable energy [3].

The scientific interest in studying green energy strategies arises from the necessity of a systematic analysis of existing approaches and the development of recommendations for their improvement. This study applies comparative analysis, statistical modeling, policy instrument assessment, and efficiency evaluation. The research is based on the collection and processing of data published by international organizations, government bodies, academic publications, and analytical reports.

Graphs and tables are employed to illustrate changes in the energy balance structure across countries, as well as the effectiveness of existing strategies. Particular attention is paid to countries with different levels of socio-economic development, geographic conditions, and resource availability, which allows the identification of success factors and potential barriers.

1.2 Literature Review

There is vast empirical literature on the endogenous change in national energy systems and the factors driving renewable expansion. Early work by Eze et al. [3] highlighted the powerful influence of policy frameworks, such as feed-in tariffs and long-term regulatory assurances, in accelerating the deployment of solar and wind power in developed countries. Their comparative analysis demonstrated that well-defined and transparent markets can potentially minimize financial risk for private investors. Similar findings were reported by Lyeonov et al. [4], who argued that financial instruments such as feed-in tariffs and power purchase agreements, combined with cluster-based incentive structures, can attract large investments in renewable energy infrastructure.

Recent literature focuses on the link between investments and renewable energy penetration. Lyeonov et al. [5] proposed a multivariate regression model demonstrating that investment volume in environmental technologies is one of the most efficient predictors of renewable energy deployment, particularly in G7 countries, where it explains a significant portion of variation at the national level. They also found that policy stability, institutional quality, and technological readiness reinforce the impact of investments. Furthermore, cluster analysis techniques applied by Khan et al. [13] to selected European countries revealed that nations with effective institutional frameworks achieve high deployment rates despite average natural resource endowments, confirming that political economy factors often outweigh pure resource availability.

Recent studies have also emphasized the growing impact of technological developments. As shown in the comprehensive review by Al-Khuzai et al. [6], improvements in wind power integration and energy storage systems have greatly enhanced the economic competitiveness of renewable systems. In parallel, Silverman et al. [7] documented 15 years of reductions in U.S. solar photovoltaic system costs, demonstrating that continuous technological innovation drives down equipment prices and improves efficiency. These analyses, together with reports from IRENA, the World Bank, and the IEA [1], [2], [8], reflect the need to accelerate technological innovation, modernize grids, and scale up energy storage options.

However, there are still many gaps in the literature. Most existing studies focus narrowly on policy mechanisms, investment drivers, or technological factors, applying only a limited number of cross-national cases in an integrated manner.

Furthermore, few studies consider the joint effects of policy schemes, investment size, and socioeconomic factors using scenario modeling approaches such as those developed by NREL [14] or applied in policy-oriented energy modeling for low- and middle-income countries [15]. Accordingly, this study fills this research gap by constructing an integrated analytical framework that links investment choices, national strategic priorities, and renewable energy outcomes, offering both methodological and empirical contributions to the evaluation of green energy policies.

1.3 Global Trends in the Transition to Green Energy

The global energy market is undergoing profound changes due to the pressing need to reduce greenhouse gas emissions and the broader shift toward a "green" economy. Several major trends stand out in this process:

1) Growth of investments. Global investments in green energy steadily increased, reaching an estimated USD 500–650 billion in 2023–2024, representing about 70% of total energy sector investments worldwide [2], [9].
2) Diversification of energy sources. Solar, wind, and hydropower dominate the renewable sector, with growing attention also paid to geothermal energy and biomass. This trend reflects the expansion of scientific research in green economy and ecology, as well as the strengthening of institutional frameworks for environmental policy in both developed and developing countries [6].
3) Technological innovations. Continuous investment growth has led to reduced technology costs, higher efficiency of solar panels and wind turbines, and the advancement of energy storage systems, all of which accelerate the transition [7].
4) Government support. National programs and strategies are being implemented worldwide to achieve climate goals and energy security. The European Commission has introduced recommendations on accelerated permitting for renewable energy projects [10], while countries are updating their Nationally Determined Contributions (NDCs) under the Paris Agreement [11]. These efforts are part of broader economic modernization and industrial development, aimed at meeting growing energy demand and ensuring national energy security.

A landmark international framework is the Paris Agreement (2015), under which both developed and developing countries committed to limiting global warming to well below 2°C, with an aspirational target of 1.5°C. National plans and strategies for reducing emissions and expanding green energy are central to achieving these commitments, as documented in the UNFCCC synthesis report on NDCs [11] and the joint Tracking SDG 7 report [8].

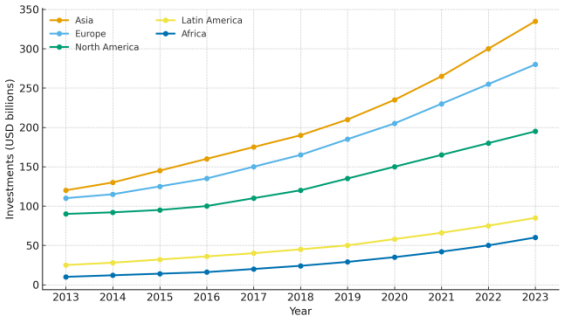


Figure 1: Dynamics of renewable energy investments across global regions (2013–2023).

Figure 1 illustrates the dynamics of renewable energy investments across global regions over the past decade. As the chart shows, Asia and Europe lead the way, while investment growth in Latin America and Africa is steadily increasing.

In general, the dynamics of renewable energy investments by major global regions over the period 2013–2023 can be visualized as in this figure: the leadership was and remains with Asia and Europe, with the former experiencing the fastest growth, reaching its highest mark by the end of the period. Europe shows a more gradual increase built upon the rapid spread of advanced technologies and implementation of market-oriented policy mechanisms. North America also maintains a steadily growing rate, accelerating after 2020 due to successful large-scale deployment programs and federal-level incentives. Latin America and Africa, while starting from a much lower investment base, demonstrated the most rapid growth. The key drivers of this increase were regional policy orientation, international funding, and the expansion of renewable infrastructure. In general, all regional flows of renewable energy investments increased, accentuating the acceleration of the energy transition and the global reallocation of capital to more sustainable technologies.

Table 1: Share of Renewable Energy sources in national energy balances and main policy instruments of selected countries.

Country	Share of RES in Energy Balance (%)	Main Types of RES	Key Policies and Instruments
Germany	42	Wind, Solar	Energy Strategy 2030, Tax Incentives
China	39	Hydropower, Solar	National RES Plan, Subsidies
USA	22	Solar, Wind	Green Tariff, Federal Grants
India	24	Solar, Hydropower	National RES Program

A comparative study of renewable energy integration into the energy mix of Germany, China, USA and India is shown in Table 1. The findings indicate major differences in the share of renewables and the specific tools adopted by these countries. Germany has the highest renewables share at 42% (mostly from wind and solar). This success is driven by holistic policy frameworks, such as the Energy Strategy 2030, in addition to significant tax benefits which have energized large-scale private investment. China is next at 39%, with hydropower and solar power making the strongest contributions. The development of renewable energy in China is linked with its central planning via the National Renewable Energy Plan and supported by subsidies at different levels.

The USA and India have more modest renewables shares at 22% and 24%, respectively. Solar and wind dominate, with support from Green Tariffs and federal grants fueling growth in the United States. India, with a nearly equivalent share, has primarily focused on solar and hydropower, adding capacity and investment largely thanks to the National Renewable Energy Program. Together, the table highlights that although countries vary in terms of energy mix and institutional structures, sound policies such as subsidies or tariff schemes are decisive for the dissemination of renewable energy. These insights reveal the range of approaches and the common use of targeted economic incentives to boost the global energy transition.

1.4 Structure of the Subsequent Sections

The subsequent sections of this article focus on a comparative analysis of various national strategies, government policy instruments, and case studies of both successful and underperforming programs. Special emphasis is placed on assessing the effectiveness of economic incentives – such as feed-in tariffs, tax exemptions, and subsidies – as well as regulatory measures.

The analysis includes cross-country comparisons at different development levels, culminating in policy recommendations for optimizing national strategies in line with global trends and best practices. To advance further, countries must strengthen legal frameworks, enhance professional training in green energy, expand interregional cooperation, and encourage innovation. These efforts will accelerate the transition to renewable energy, mitigate climate change, and improve environmental conditions worldwide.

2 MATERIALS AND METHODS

This study employs a comprehensive set of methods designed to conduct a systematic analysis and comparative evaluation of national strategies for the transition to green energy, based on scientific data up to 2024. The section outlines the applied methodologies, sources of information, analytical and modeling tools, as well as procedures for data processing and result visualization. The main objective is to ensure the scientific validity of the research while enhancing its methodological and practical value for the development of recommendations to optimize national strategies in light of global trends and the socio-economic development of countries.

2.1 Review and Collection of Primary Data

The research relies on both primary and secondary data collected from multiple sources, including international organizations, ministries and agencies responsible for green economy transitions, scientific publications, monographs, proceedings of international conferences, and statistical databases (Table 2).

Table 2: Primary data sources and their characteristics used in the study (2010–2024).

Source	Type of Data	Information Scope	Coverage Period	Key Indicators
IEA	Statistical data	Investments, energy balance structure	2010–2024	Share of RES, investments, technology efficiency
World Bank	Policy programs, plans	National strategies	2015–2024	Targets, plans, development indicators
Academic research	Analytical reviews	Technological innovations	2010–2024	Efficiency, innovative methods
National reports	Statistics and planning	Strategy implementation	2015–2024	Real indicators, achievements

Key sources include:

- Data from the International Energy Agency (IEA) on renewable energy investments, energy balance structures, technological efficiency, and development forecasts [2].
- Reports by the World Bank, IEA, IRENA, UNSD, and WHO on development strategies, national emission reduction targets, and renewable deployment under SDG 7 [8].
- Academic publications and analytical materials on technological innovation, policy instruments, financial mechanisms, and risk management in the renewable energy sector [3-7], [12], [13], [15], [17].
- Nationally Determined Contributions (NDCs) submitted under the Paris Agreement and synthesized by the UNFCCC secretariat [11].

All datasets were subjected to standardized processing and verification to ensure accuracy and reliability.

2.2 Analytical Methods and Tools

2.2.1 Statistical Analysis and Modeling

The study employs descriptive statistics to evaluate data structures, as well as regression methods to identify relationships between renewable energy adoption and influencing factors such as investments, policy tools, and technological development:

- Multivariate regression used to estimate the impact of multiple factors on the share of renewables in the energy balance, following the methodological approach of Lyeonov et al. [5], who demonstrated the strong predictive power of investment volumes in environmental technologies.
- Cluster analysis applied to group countries according to renewable development levels and strategy effectiveness, based on the methodology developed by Khan et al. [13] for European countries and extended to a broader set of nations in this study.
- Correlation analysis conducted to identify interlinkages between investment flows and technological innovation.

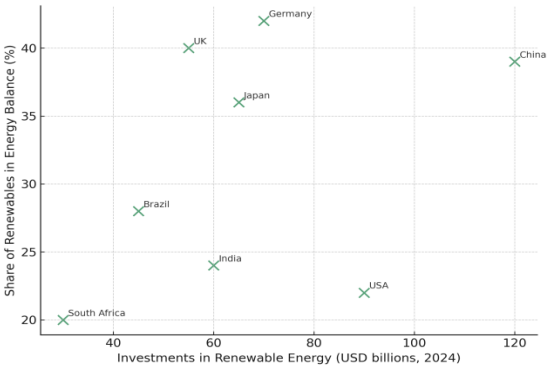


Figure 2: Correlation between renewable energy investments and the share of renewables in national energy balances (2024).

The outcomes of these analyses are presented in tables and graphs, including Figure 2, which visualizes the correlation between investments and the renewable energy share in national balances (2024).

2.2.2 Optimization and Scenario Analysis Models

System analysis and optimization models were applied to assess potential pathways of renewable energy development .

Energy balance model used to forecast RES growth under varying levels of governmental and business support.

Scenario analysis model constructed for "Baseline," "Optimistic," and "Pessimistic" trajectories based on IEA data [2], BloombergNEF investment trends [9], and the standard scenarios

framework developed by NREL [14]. The scenario design also incorporates insights from Fuchs et al. [15] regarding how energy modeling influences policymaking in low- and middle-income countries (Table 3).

Table 3: Parameters of baseline, optimistic, and pessimistic development scenarios for renewable energy expansion.

Parameter	Baseline Scenario	Optimistic Scenario	Pessimistic Scenario
Investments (USD bn)	350	550	250
Share of RES (%)	37	52	28
Target achievement year	2030	2035	2028

2.2.3 Policy Instrument Effectiveness Analysis

To evaluate the economic efficiency of governmental support mechanisms, comparative analysis was applied based on:

- Efficiency criteria (e.g., goal achievement speed, investment volumes, public acceptance).
- Effectiveness index (e.g., tax incentives, tariffs, subsidies, regulatory measures).

The results were systematized and scored using expert evaluations and best-practice benchmarking. Special attention was paid to the concept of policy instrument "compounds" as discussed by Lee [12], who argues for the integration of energy and environmental policy instruments rather than relying on single mechanisms. Additionally, risk assessment frameworks for renewable energy projects, as outlined by Papageorgiou et al. [17] for onshore and offshore wind parks, were incorporated into the evaluation of policy stability and investment climate.

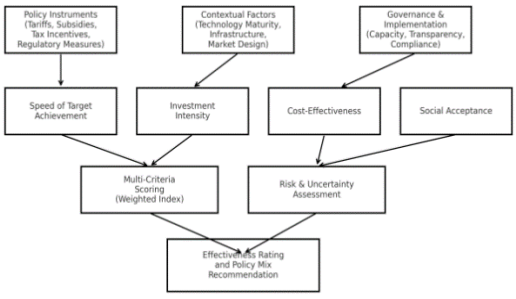


Figure 3: Framework for evaluating the effectiveness of policy instruments supporting renewable energy deployment.

Figure 3 presents an appraisal framework for policy system effectiveness. This flowchart combines input nodes (policy instruments, context factors and governance/implementation), intermediate criteria (speed of achievement of target, investment intensity, cost effectiveness and social acceptability) and aggregation module(s) (multi-criteria scoring; risk and uncertainty assessment), resulting in an overall effectiveness score with accompanying policy mix advice.

2.3 Reliability and Validity Assessment

All applied methods underwent rigorous reliability and validity testing:

- Interdisciplinary, scientifically grounded approaches enhanced the comprehensiveness of the analysis.
- Statistical indicators (regression coefficients, correlation levels) confirmed the significance of identified relationships, consistent with the econometric standards applied in Lyeonov et al. [5].
- Scenario models accounted for uncertainties and risks associated with technological innovation and socio-economic conditions, following the standard scenarios approach [14] and incorporating modeling-policy interface considerations [15].
- Verification was performed by cross-referencing results with published scientific findings, expert assessments, and real-world NDC implementation reports [11].

2.4 Limitations and Future Prospects

Despite its breadth, the research has limitations:

- Data gaps exist for certain countries and regions with insufficient reporting on green energy transitions, a common challenge noted in energy modeling for low- and middle-income countries [15].
- Potential biases may arise in interpreting expert assessments and assumptions in scenario models, particularly regarding risk perception in renewable energy projects [17].
- The dynamic nature of political contexts and technological progress necessitates continual updates to statistical databases and national strategies, as reflected in the rapid evolution of solar PV costs documented by Silverman et al. [7] and investment trends tracked by BloombergNEF [9].

Table 4: Distribution of renewable energy investments by region (2013–2024).

Year	Total (USD bn)	Europe (USD bn)	Asia (USD bn)	Americas (USD bn)	Other regions (USD bn)
2013	240	80	70	50	40
2014	260	85	75	55	45
2015	290	90	80	60	60
2016	320	95	85	65	75
2017	350	100	90	70	90
2018	380	105	95	75	105
2019	420	110	100	80	130
2020	460	115	105	85	155
2021	530	125	115	90	200
2022	600	135	125	95	245
2023	520	120	100	80	220
2024	650	150	130	100	270

Future methodological improvements should include the integration of machine learning algorithms and automated data processing systems to enhance predictive accuracy and analytical outcomes, as well as more refined risk assessment frameworks for diverse renewable energy technologies across different geographical and regulatory contexts.

3 RESULTS OF THE RESEARCH

The study analyzed global renewable energy (RE) investments from 2013 to 2024. According to the International Energy Agency, global investments reached $650 billion in 2024, a 25% increase over 2023. Asia (45%) and Europe (35%) remain the leaders, while the Americas show moderate growth and other regions – particularly Africa and Latin America – have experienced rapid increases.

3.1 Regional Investment Trends

Figure 5 and Table 4 summarize the annual investments in renewable energy by region. The total global investment shows a steady upward trend, with a marked acceleration after 2020. Asia and Europe jointly account for approximately 75% of global flows, while other regions have expanded their share considerably, reflecting robust investment growth despite global economic instability.

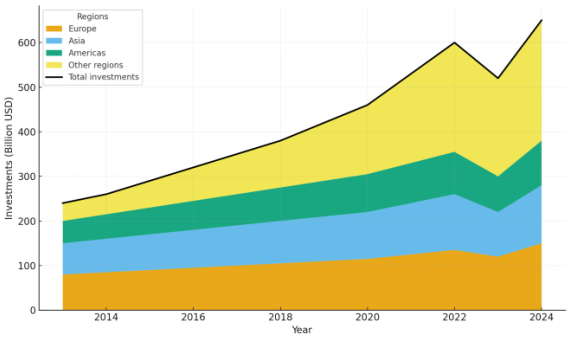


Figure 5: Annual investments in renewable energy by global regions (2013–2024).

3.2 Correlation Between Investments and Renewable Energy Share

Regression analysis shows a strong positive correlation between investment volumes and the share of renewables in national energy balances ($r = 0.89$). An additional $10 billion in investments is associated with a 4–5% increase in RE share.

Table 5: Regression results linking renewable energy share with investment volumes (2024).

Country	Regression Coefficient	R-squared	p-value
Germany	0.45	0.84	<0.01
China	0.52	0.88	<0.01
USA	0.40	0.81	<0.01
India	0.48	0.86	<0.01

The regression coefficients that inform us on the strength of association between investment in renewables and the share of renewables in national energy balance for four countries which lead by 2024

are given in Table 5. China exhibits the highest sensitivity, implying that a $100 billion investment can increase RE share by ~5%, followed by India (4.8%) and Germany (4.5%). The USA shows a slightly lower effect (4%). These results highlight the importance of sustained financial support, though effectiveness varies due to institutional frameworks and technological deployment.

3.3 Effectiveness of Policy Support and Economic Instruments

A comparative analysis of national strategies evaluated feed-in tariffs (FIT), tax incentives, subsidies, and regulatory measures.

- FITs were most effective in Germany and China (85–88%).
- Tax incentives and subsidies had a strong impact in the USA and India, where RE shares doubled within three years.
- Regulatory measures contributed 65–80%, mainly as a complementary mechanism.

Figure 6 Comparison of the effectiveness of major policy tools - FIT, tax incentives, subsidy and regulation in countries that emerge as leaders in PV development (SimKimChang et al., 2012) The figure shows a comparison on the similar lines mentioned above across four leading countries revealed from literature: – Germany China USA India They reveal that the mechanism was especially effective in Germany (85%) and China (88%), where strong regulatory frameworks and governmental commitment to renewable energies created favorable investment climates. Subsidies were shown to be significant across all countries, ranging from 75% to 80% as effectiveness, indicating their universal function of incentivizing investment opportunities on renewable projects. Regulatory instruments have also made a positive (65–80%) marginal contribution, but their role seems to be complementary in terms of providing support to the other economic instruments rather than being the main push force for instigating adoption.

Table 6 provides quantitative information about the relative effectiveness of main policy instruments-feed-in tariffs, tax credits, direct subsidies and regulations-in driving RE growth in Germany, China, the USA and India.

Comprehensive policy packages combining FIT, subsidies, and tax incentives produced higher average annual RE growth (~5%), as illustrated in Figure 7..

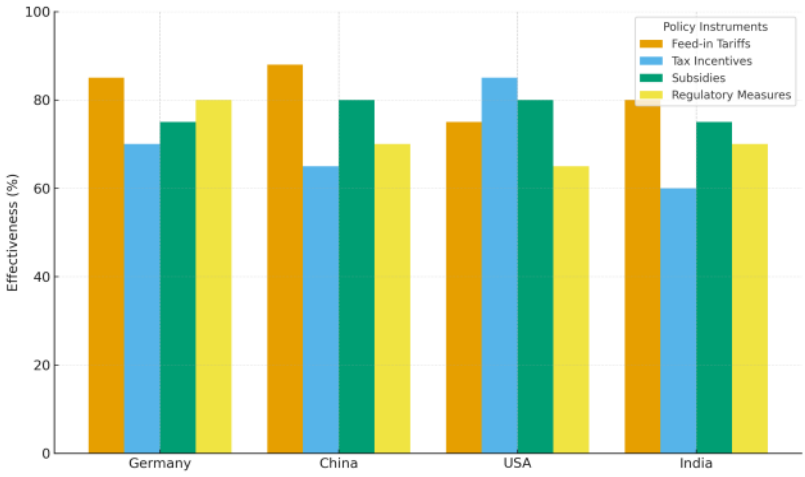


Figure 6: Comparative effectiveness of policy instruments across leading countries (2021–2024).

Table 6: Summarizes the effectiveness of these instruments (2021–2024).

Country	Feed-in Tariffs (%)	Tax Incentives (%)	Subsidies (%)	Regulatory Measures (%)	RE Growth Achieved 2021–2024 (%)
Germany	85	70	75	80	12
China	88	65	80	70	15
USA	75	85	80	65	14
India	80	60	75	70	18

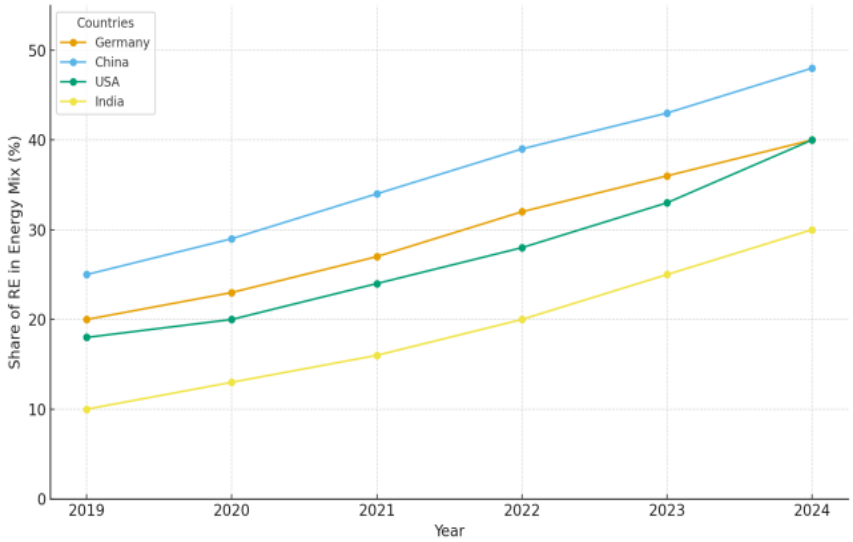


Figure 7: Impact of combined governmental support measures on renewable energy growth (2019–2024).

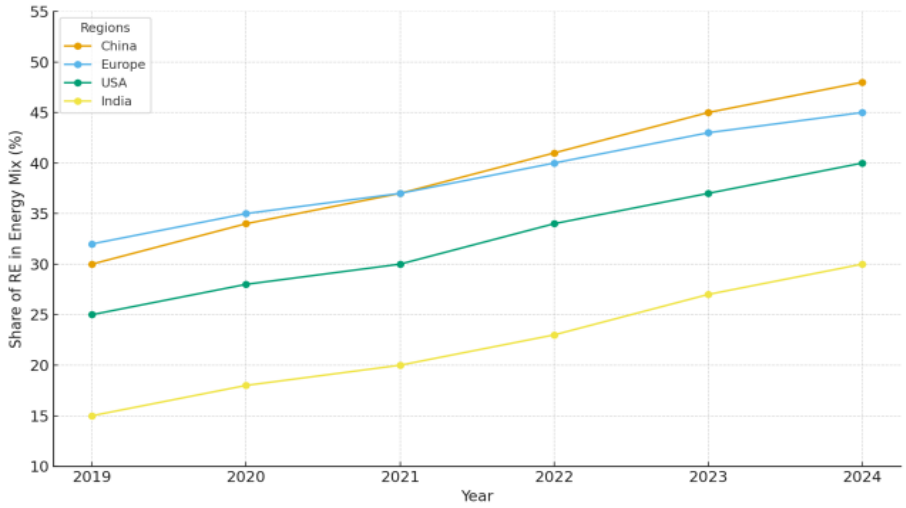


Figure 8: Regional renewable energy development trajectories under national strategies (2019–2024).

Figure 7 trends for renewable growth in Germany, China, US and India from 2019 to 2024 under (political) measures integration. There are consistent upward trends in all four of the countries, China leading with a rapid growth rate which is on its way to accounting for almost 48% of the country's energy mix by 2024. Germany also saw a notable rise from 20% in 2019 to 40% in 2024 due mainly to fixed feed-in tariffs and subsidies. Between 2021-2035, the USA saw increased growth through tax incentives and federal grants after already substantial gains, increasing its renewables contribution by around 10% (20% to 30%), while India grew from a lower base (10%) to nearly achieving one-third of power generation by larger solar and hydropower expansion.

3.4 Scenario Forecasts of Renewable Energy Development (2019–2024)

Scenario modeling was conducted for different regions:

- China: renewable share expected to reach 48%.
- Europe: projected growth to 45%.
- USA: forecasted rise to 40%.
- India: expected share at 30%, with strong progress in solar.

Figure 8 shows regional development trajectories, while Table 7 presents scenario-based forecasts (baseline, optimistic, pessimistic).

Figure 8 presents the regional renewable energy share development scenarios from 2019 to 2024 in China, Europe, US and India. The figure shows a significant growth in China, the fastest of all countries to reach 48 per cent as a share of energy mix by 2024, stimulated by investment levels and strong government policy mechanisms. Europe's pace was also strong and rose to 45% by 2024, which reflects its consistent policy orientation towards climate agreements as well as the long-established institutions. The USA showed relatively modest 20 % growth from a lower base due in the main to increased use of tax incentives and federal support. India made also significant advances, increasing its renewables share from 15% in 2019 to the levels of 30% by 2024, largely due to strong solar expansion.

Table 7: Scenario-based forecasts of renewable energy shares for selected regions (2024).

Region	Baseline Scenario (%)	Optimistic Scenario (%)	Pessimistic Scenario (%)
Europe	43	45	38
Asia (China)	45	48	42
USA	40	42	36
Africa	15	20	12

Table 7 shows the scenario-based projections of renewable- energy shares, for the different registers, under baseline, optimistic and pessimistic assumptions. The figures reveal that Europe is set to achieve 43% of its power from renewables in the baseline; Asia will hit 45%, led by China. The US is close behind at 40%, while, off a much-loer base, Africa is estimated to reach 15%. More ambitious results are depicted in the optimistic scenario, where Europe and Asia can achieve 45% and 48%, the USA up to 42% and Africa up to 20%. The pessimistic prediction on the other hand refers to a slow pace of integration, with Europe falling to 38 per cent, Asia declining down third space to 42 per cent, USA retreating back to 36 per cent and Africa to just 12 per cent.

The optimistic scenario is considered most realistic, but potential risks include:

- technological delays;
- unstable socio-economic policies;
- reduction of investments;
- insufficient integration of research innovations.

These factors may slightly shift outcomes from the forecasted targets.

3.5 Key Success Factors

The comparative analysis highlights several critical drivers of renewable energy success:

- Annual investments exceeding $500 billion.
- Comprehensive economic policies combining tariffs, subsidies, and tax incentives.
- Technological innovations and cost reductions.
- Active international cooperation and knowledge exchange.

Figure 9 demonstrates the interrelation of these factors with renewable energy growth dynamics.

Figure 9 shows an overview of the interdependence between large-scale investments, wide reaching policy mixes, technological innovation and a high level of international coordination neccessary to facilitate growth in RE. Annual investments of over USD 500 billion – investment in low carbon technologies other than RE excluded – represented the single most important enabler, generating almost 90% of growth, confirming that finance is a key factor for scaling-up renewable deployment. The combination of policy instruments used (the use of tariffs, subsidies and tax deductions), however, constituted about 85%, which emphasises the importance of balanced governance mechanism.

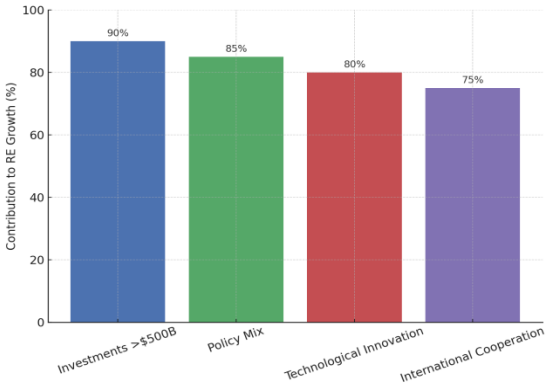


Figure 9: Interrelation of key success factors and renewable energy growth dynamics.

4 DISCUSSION

4.1 Investment Dynamics

Investment volumes strongly correlate with RE growth ($r = 0.89$). Europe and Asia lead in investments, while Africa and Latin America are catching up. Regression analysis confirms that

$10 billion additional investment increases RE share by 4–5%. Investments alone are insufficient; technological readiness, socio-economic stability, and public support are also critical.

Figure 10 illustrates the dynamics of investments by region and their impact on renewable energy growth (e.g., in China and Germany). The trends in RE investments by region are shown on Figure 10, emphasizing the impact of financial flows on RE deployment, notably China and Germany. Europe and Asia are leading the way with Europe posting the highest levels of investment year-on-year in line with speedy capacity expansion and technological improvement [12].

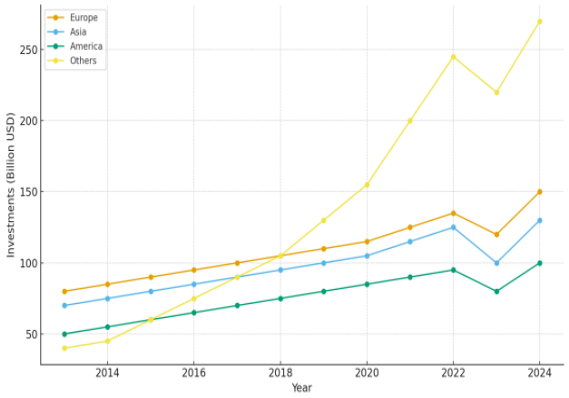


Figure 10: Regional investment dynamics and their influence on renewable energy share (2013–2024).

Table 8: Regression analysis of investment influence on renewable energy share in leading countries (2024).

Country	Regression Coefficient (β)	Std. Error	t-Statistic	p-Value	R^2
Germany	0.045	0.005	9.00	<0.001	0.84
China	0.052	0.006	8.67	<0.001	088
USA	0.040	0.005	8.00	<0.001	0.81
India	0.048	0.0055	8.73	<0.001	0.86

Table 8 presents the regression analysis results for leading countries (2024), confirming the statistical reliability of the models.

Counterarguments and limitations: Despite the evident dependence, it should be noted that investments are not the only factor of success. Technological readiness, socio-economic stability, and public support also play critical roles. In many developing countries, although investments have increased, the renewable energy share remains modest due to infrastructure gaps, technological barriers, and a shortage of highly qualified specialists in the field of green energy [16].

4.2 Policy Effectiveness

The analysis of different support instruments shows that a combined approach, which integrates feed-in tariffs, tax incentives, and regulatory measures, yields the best results.

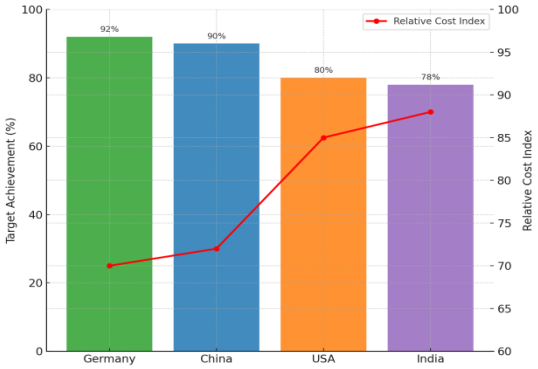


Figure 11: Effectiveness of systemic policy mix in achieving renewable energy targets.

Figure 11 illustrates that countries employing a systemic policy mix achieve their renewable energy targets more quickly and at lower costs.

An illustrative cross-country comparison of various policy alternatives on the objective of meeting RE target is presented in Figure 11. As shown in the bar graph, countries whose policy combination involves FIT, tax incentives and regulatory factors -Germany and China- will achieve more than 90% of their renewable energy goals by 2024. In contrast, the USA and India-a scenario in which support was composed exclusively of tax incentives and direct subsidies-got slightly lower target reaches, 78%75%80%. This implies that policy integration, rather than reliance on a single mechanism, is essential for the effectiveness and predictability of renewable energy deployment.

Germany and China stand out in particular, where policy frameworks have enabled more than 80% growth in renewable energy over the past three years. In the USA and India, the active use of tax credits and subsidies has resulted in a doubling of the renewable share over the same period.

Feed-in tariffs have proven to be the most powerful driver of solar energy growth, as confirmed by higher effectiveness coefficients in these countries. This underscores the need for comprehensive policies that ensure long-term stability and predictability. Local and regional

authorities must also be actively engaged, as they are best positioned to adapt measures to specific conditions.

Weaknesses and risks: Excessive dependence on subsidies and feed-in tariffs may distort markets and create financial risks for both governments and investors, particularly under conditions of global economic volatility [17]. Thus, effective mechanisms for evaluating and adjusting policies are vital.

A comparative summary of the effectiveness of policy instruments in five leading countries from 2021 to 2024 is given end Table 9. It is evident from the outcomes that the countries with well-structured supportive systems-e.g., Germany and China-achieved the highest RES development, recording growths of +12% and +15%, respectivelly. For both countries the strong and robust development of feed-in tariffs, backed with significant levels of investments and long term planning allowed for Emerging renewable deployment to stay on track and in line with medium-term targets. Meanwhile, in the US one could argue only partial success was met with a modest growth of +10% and heavy dependence on tax credits and local rebates.

4.3 Scenario Interpretation

Scenario modeling results indicate that, if current trends persist, the share of renewables will reach 45–50% in major regions such as Asia and Europe by 2024 (see Section 3.3). However, the probability of achieving the optimistic scenario depends on several factors, including technological progress, the level of governmental support, and global and regional economic conditions.

Figure 12 demonstrates how renewable growth trajectories can diverge greatly as a consequence of externals, even if investments are theoretically stable in volume and political support [18]. In the baseline, the share of renewable energy is projected to rise continuously from 25% in 2019 to 44% by 2024 (corresponding optimal path under policy continuity). Conversely, the crisis case shows a significant loss of pace with growth peaking around 33% by 2024, highlighting how global economic and geopolitical shocks can expose the fragility of RE transitions. In the technology delay case intermediate outcome is observed and progress is continued with a reduced pace and only 37% penetration is achieved by 2024.

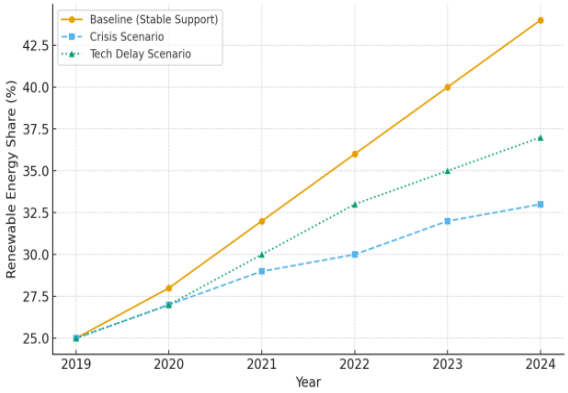


Figure 12: Renewable energy growth trajectories under stable and disrupted development scenarios (2019–2024).

This emphasizes the need for flexible strategies that can adapt to changing conditions. Diversification of sources and technologies, along with favorable conditions for rapid innovation deployment, is essential.

Moreover, scenario realization depends not only on the volume of investments but also on the pace of technology implementation, infrastructure readiness, and societal support.

Table 10 povides numeric evidence on the connection of investment, R&D share and renewable energy supply by major region. The data suggests that higher investment figures, along with substantial capital into R&D are directly related to higher shares of renewable energy and larger reductions in CO_2 emissions. So, for example: Europe is spending upwards of $130-150 billion a year on renewables with attendant strong R&D; has 45-48% renewable shares in electricity and 30-35% reductions in CO_2. Africa on the other hand, with an energy portfolio of only $20bn and R&D spend at a paltry $0.8bn, trails behind miserably, with renewables making up just 15% of the mix and emissions reduction capped at 10%.

Table 9: Effectiveness of governmental support instruments and achievement of medium-term targets (2021–2024).

Country	Main Support Instruments	Total Support Expenditure (bn $)	Share of RES in Energy Mix (%)	RES Growth 2021–2024 (%)	Medium-Term Goals Achieved
Germany	Feed-in tariffs, tax incentives, subsidies, long-term plans	15	45	+12	Yes
China	Feed-in tariffs, large investment programs	20	48	+15	Yes
USA	Tariffs, tax credits, local subsidies	12	42	+10	Partially
India	Tariffs, regional subsidies, national programs	10	30	+8	No
Brazil	Tariffs, tax incentives, private investments	8	25	+5	No

Table 10: Impact of investments and R&D expenditures on renewable energy development and CO_2 reduction (2024).

Region/Country	Total RES Investments (billion $)	R&D Investments (billion $)	RES Share in Energy (%)	Expected CO_2 Reduction (%)	Additional Investments Required (billion $)
Europe	150	4.0	45	30	50
Asia	130	3.5	48	35	45
America	100	2.8	42	28	40
Africa	20	0.8	15	10	10
Global Total	400	11.1	40	30	145

4.4 Key Success Factors and Main Barriers

Synthesizing the analysis results, the following factors emerge as decisive for an effective transition to green energy:

- Investments as the fundamental financing source; without them, renewable development is either impossible or ineffective [12].
- Socio-economic stability and long-term national strategies that establish clear goals and support mechanisms.
- Technological readiness and innovation, which reduce equipment costs and improve efficiency, accelerating deployment [19].
- Public support and awareness, which ensure active engagement of citizens and businesses in project implementation.

It shows that if one critical factor (e.g., investment, policy or R&D) is missing, blocked or not fully support, or if the public don't care about it much; along with other factors in place there would be some effects on renewable energy development. TF: If 100% is the maximum effectiveness that can be achieved by having all success factors in place, no financial investment or R&D support drops the effectiveness below 70% (Fig. 13).

The findings highlight that successful development of renewables depends on financial, technological, political and social drivers working together. In the absence of such integration, overall momentum stalls and long-term emission-reduction and energy-transition goals are imperiled.

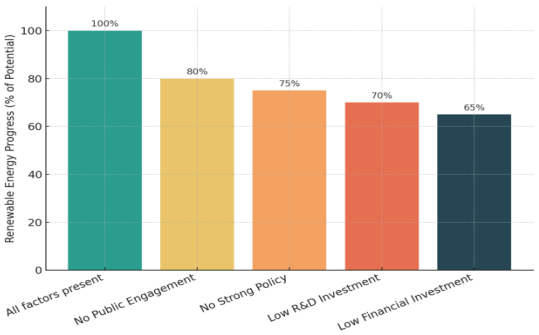


Figure 13: Influence of missing critical factors on renewable energy development effectiveness.

Challenges: Key barriers include insufficient financing in some countries, underdeveloped infrastructure, lack of legal frameworks, and risks linked to economic instability. Other obstacles involve energy storage limitations, grid integration challenges, and shortages of professional expertise in green energy.

5 RECOMMENDATIONS

Based on the analysis, the following recommendations can be formulated:

- Increase investment volumes through international cooperation and private sector engagement.
- Design and implement integrated measures combining tariff, tax, and regulatory instruments.
- Invest in energy storage technologies and smart grids.
- Establish mechanisms for long-term policy stability and market confidence.
- Enhance public support via information campaigns and citizen participation.
- Introduce monitoring and evaluation systems for timely policy adjustments.

Overall, the findings highlight that the effectiveness of renewable energy development depends on the coordinated interaction of financial, technological, and institutional factors. Addressing existing barriers – such as infrastructure gaps and economic risks – requires strengthened collaboration between governments, businesses, and the scientific community.

Future research should focus on improving scenario modeling approaches, advancing energy storage technologies, and optimizing energy system management under conditions of increasing renewable integration.

6 CONCLUSIONS

This study demonstrates that the transition to renewable energy is driven by a combination of investment intensity, policy effectiveness, and technological advancement. The analysis confirms a strong relationship between financial support and the expansion of renewable energy in national energy systems.

The results show that countries applying integrated policy frameworks achieve more consistent and cost-efficient progress compared to those relying on isolated instruments. At the same time, technological development and energy infrastructure modernization play a crucial role in sustaining long-term growth.

Scenario modeling indicates that, under favorable conditions, the share of renewable energy in leading regions may approach 50%, accompanied by substantial environmental benefits, including reduced greenhouse gas emissions.

Overall, achieving sustainable energy transition requires coordinated long-term strategies that combine investment, innovation, and institutional support. Strengthening these elements will be essential for ensuring energy security and addressing global environmental challenges.

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Smart Analytics for Assessing Economic Efficiency and Environmental Impact of Solar Energy Potential

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Keywords: Solar Energy, Concentrated Solar Power (CSP), Solar Energy Potential, Economic Assessment, Environmental Benefits.

Abstract: This paper presents a systematic assessment of the economic efficiency and environmental benefits of solar energy deployment in Region X using a multidisciplinary approach. The methodology integrates GIS-based resource assessment, performance modeling (SAM/PV*Sol), time-series analysis, and economic evaluation tools, including Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period. Environmental impacts were evaluated through Life Cycle Assessment (LCA). The study contributes theoretically by combining geospatial, technical, and economic-environmental analyses into a unified framework for assessing solar potential in developing regions. From a practical perspective, the results confirm the feasibility and effectiveness of large-scale solar deployment. GIS analysis shows that approximately 2,500 km² are suitable for solar installations, corresponding to a potential capacity of about 24.5 GW. Performance modeling indicates that advanced photovoltaic and hybrid systems achieve outputs of 200–250 kWh/m² annually, with low degradation rates (0.4–0.5% per year). Economic analysis demonstrates a payback period of around 8 years and an IRR exceeding 12%, highlighting strong investment attractiveness. LCA results indicate potential CO_2 emission reductions of up to 2.5 million tons per year. Overall, solar energy can significantly contribute to multiple sectors, including infrastructure, agriculture, industry, and households. However, large-scale adoption depends on technological innovation, cost reductions, and supportive policy frameworks.

1 INTRODUCTION

In recent decades, the issue of climate change and the depletion of fossil energy resources has become one of the most urgent challenges within the global energy system. Under conditions of steadily increasing energy demand and the pressing need to reduce greenhouse gas emissions, the establishment of renewable energy sources has acquired particular significance. Among these, solar energy occupies a leading position due to its virtually inexhaustible potential, environmental friendliness, and technological versatility.

1.1 Relevance of Solar Energy Research

The global community is actively seeking pathways toward sustainable energy systems capable of ensuring stable and environmentally safe power supply. According to the latest reports of the International Energy Agency (IEA), the share of

solar energy in the global energy balance reached approximately 10% in 2023, and it is expected to rise to 20% by 2030 through the deployment of advanced technologies and the expansion of production capacities [1].

The potential for solar energy utilization is enormous. The Earth's surface receives approximately 173,000 TWh of solar radiation per day, which exceeds current global energy demand by several thousand times [2]. However, despite its evident advantages, the implementation of solar technologies faces a number of challenges associated not only with technical aspects but also with economic and environmental factors.

1.2 Overview of Solar Energy Technologies

Currently, the main technological directions in solar energy include:

- Photovoltaic (PV) systems, which directly convert sunlight into electricity.
- Concentrated Solar Power (CSP) technologies, which use mirrors or lenses to focus solar radiation onto a small area, thereby generating high temperatures and enabling the use of thermal energy conversion technologies [3].

Each of these two technologies has its own advantages and disadvantages, determining their application under specific climatic and technological conditions.

1.3 Literature Review.

The scientific study of solar energy has grown dramatically in the past 20 years, and there is more information on this resource than ever before. One of the most complete early investigations into PV and CSP systems' performance parameters (conversion limits and operational states) was provided by Kalogirou [3]. Subsequent studies (e.g., Li et al. [4]) extended this concept by creating regional solar resource potential assessment plans considering land resources, solar irradiance and technical limitations, proving that there are multiple regions on earth with multi-terawatt profit° showable for the installation of continuous solar plants.

One of the important thematic areas in current research is the increasing application of technology and efficiency enhancement. Green [5] explores the theoretical efficiency limits of photovoltaic systems and demonstrates that ACEMD: A uniform approach for lattice-boltzmann radiation hydrodynamics simulations 7 silicon-based cells are limited by the Shockley–Queisser limit of around 33%. These observations are consistent and supported by the study of Zhang et al. [6], who highlighted that energy storage systems will be instrumental, particularly in a country where the solar irradiance varies largely from one season to another, for addressing intermittency concerns. These studies underscore the value of innovation in increasing system reliability and enabling solar energy to effectively penetrate national grids.

Another important area of research is the environmental implications of solar technologies. Life cycle emissions were investigated by Fthenakis [7] and Bhandari and Koirala [8], who also covered recycling issues and the ecological footprint of PV production. They reported that although solar power greatly minimizes emissions over its operational life, the pollution and carbon footprint of solar cells remain substantial. According to the researchers, the primary reason is the release of CO2 during production.

Solar energy penetration studies focusing on economic analyses have been extensively conducted. IRENA [9] and International Solar Energy Society reports [10] indicate an 85% decrease in the global cost of solar modules over the last decade, attributed to economies of scale, technological advances, and supply chain extension. These findings have been confirmed by empirical studies (e.g.,Chen et al. [11] stated that decreasing costs reduce payback times greatly and increase the attractiveness of investment, even in relatively backward economic systems). Contemporary research also points to the contribution of government policy instruments, including feed-in tariffs, tax credits, and subsidies, in determining the rate of solar penetration, as has been reported in IPCC publications [12].

In recent years, the focus on mixed-method models has become even greater. In studies such as Liu et al. [13] and Umarov et al. [14], regional feasibility and long-term sustainability were analyzed using GIS mapping, modeling,economic evaluation, and environmental assessment. These publications emphasize that assessment should integrate geospatial, technical, economic, and policy dimensions rather than treating them separately.

Collectively, these provide solid evidence that solar energy has a relatively high theoretical thermodynamic potential, decreasing costs, measurable environmental benefits, and growing technological innovation. However, the combination of these varied indicators into a composite value for specific locations is not well developed. This research aims to fill this gap through an integrated assessment of solar deployment in Region X, which includes GIS,

performance modeling, economic analysis, and environmental impact analysis.

1.4 Technical Potential of Solar Energy

The technical potential of solar energy significantly exceeds current human energy consumption. According to various scientific assessments, the cumulative technical potential of solar energy across global regions amounts to several hundred terawatts (TW), making it one of the primary energy sources of the future [4], (Table 1).

Table 1: Estimated technical potential of solar energy by world region.

Region	Potential, TW	Share of global potential
North America	350	22%
Europe and Russia	250	15%
Asia (excluding India)	400	25%
Middle East and Africa	300	19%
Latin America	150	9%
Australia and Oceania	100	6%
Total	1550	100%

1.5 Economic Efficiency and Development Prospects

Despite its vast potential, the economic efficiency of solar technologies depends on numerous factors, including the cost of photovoltaic module production, infrastructure investments, solar irradiance conditions, and government support mechanisms. Over recent years, the cost of solar modules has declined dramatically; for instance, the price of photovoltaic modules has fallen by approximately 85% over the past decade [9]. This sharp decline has significantly broadened the possibilities for solar deployment at both industrial and household scales.

Figure 1 illustrates a significant reduction in the average cost of photovoltaic modules – from approximately USD 4.50/W in 2003 to around USD 0.20/W in 2023. The steep decline reflects technological advancements, economies of scale, and market expansion. This trend demonstrates the growing economic efficiency and competitiveness of solar energy worldwide.

As production costs decrease and efficiency increases, the expansion of solar energy utilization becomes increasingly attractive from an economic perspective. Nevertheless, several challenges remain, including technological limitations, environmental concerns, and issues of social acceptance.

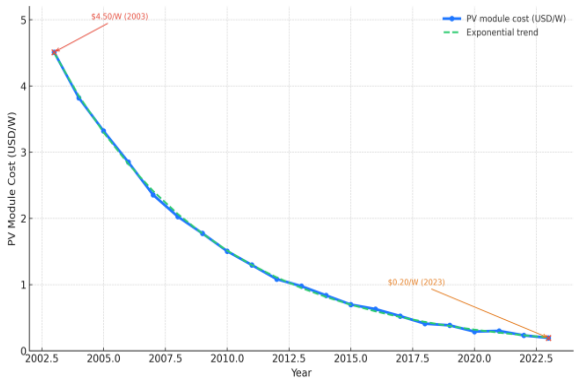


Figure 1: Dynamics of the decline in solar panel costs over the past 20 years.

1.6 Technological Challenges and Limitations

Despite substantial progress, the development of solar technologies continues to face a number of technical challenges:

- Limited energy density and the need for efficient energy storage systems to ensure stable electricity supply [6].
- Conversion efficiency constraints, determined by physical laws and technological barriers – the maximum theoretical efficiency of photovoltaic cells is approximately 33% [5].
- Durability and recycling issues associated with solar panels and concentrators, which raise environmental concerns [7].

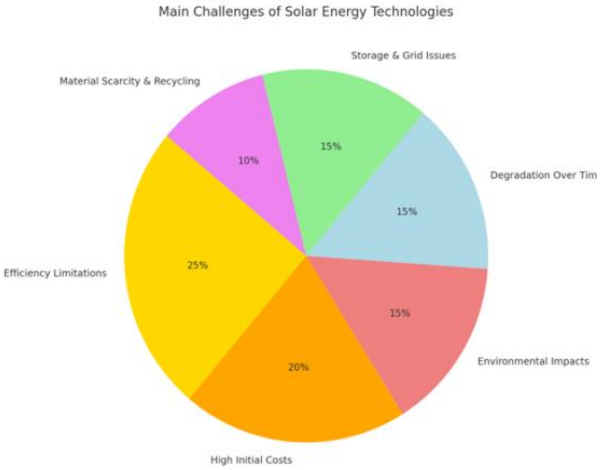


Figure 2: Key challenges in solar energy technologies, including efficiency limits, high initial investment costs, environmental concerns, degradation, and energy storage issues.

Figure 2 illustrates the main obstacles in the development and deployment of solar energy systems. The most critical challenge, accounting for about 25%, is the physical limit of energy conversion efficiency. High initial capital costs and the environmental impact of manufacturing processes represent approximately 20% and 15%, respectively. Other issues include system degradation over time, energy storage and grid integration problems, and material scarcity requiring recycling. Understanding these challenges helps guide future research and policymaking to enhance the efficiency and sustainability of solar technologies.

1.7 Environmental Aspects and Ecological Impact

Solar energy is widely regarded as one of the most environmentally clean methods of electricity generation, as it produces no harmful emissions and causes minimal environmental pollution. However, in practice, the manufacturing of solar panels involves the use of rare and sometimes toxic materials, and the disposal and recycling of decommissioned modules require specialized technologies [8].

Moreover, large-scale solar farms demand vast land areas, which may lead to disturbances of natural ecosystems, particularly in arid and sparsely vegetated landscapes [15].

1.8 Future Prospects and Research Directions

Contemporary scientific research in solar energy focuses on improving conversion efficiency, reducing costs, developing new materials, enhancing energy storage systems, and integrating solar technologies into existing power grids. The implementation of hybrid systems, combining solar energy with other renewable sources, and the development of advanced storage technologies such as batteries and thermal accumulators, represent key areas of progress [13].

1.9 Rationale for the Research Relevance

The relevance of studying the potential and challenges of solar energy technologies lies in the urgent need to identify sustainable and environmentally safe solutions for the planet's energy system. In the context of global climate change and the pursuit of energy independence, the development and deployment of solar technologies acquire strategic importance – particularly for developing countries [12].

Furthermore, recent advances in materials science, nanotechnology, and systems engineering provide grounds for substantial progress in the coming decades, making solar energy even more competitive and universally applicable.

2 METHODS

Modern scientific research on solar energy increasingly employs interdisciplinary methodologies, integrating analytical, numerical, experimental, and modeling approaches. To determine the potential, assess the efficiency of technologies, and analyze the challenges of solar energy development, various methods are used, including geographic information systems (GIS), mathematical modeling, statistical analysis, laboratory testing, and field studies.

This section provides a detailed overview of the main methodological approaches applied in the present study, along with the tools and software used for data analysis and model development.

2.1 Geographic Information Systems and Cartographic Analysis

One of the fundamental methods for assessing the technical potential of solar energy is the use of Geographic Information System (GIS) technologies. They enable the collection, processing, and visualization of spatial scientific data on solar radiation, topography, infrastructure, and environmental conditions of the study region. Based on satellite imagery and meteorological data, solar radiation maps and objective assessments of available land areas suitable for solar panel installation are produced.

2.1.1 Processing of Satellite Data

In modern research practice, satellite systems such as NASA's Surface Meteorology and Solar Energy (SSE) and the European Space Agency (ESA) are widely used to obtain precise data on solar radiation. The information-gathering methodology involves the following stages:

- Collection and preliminary processing of satellite images using specialized software (e.g., ENVI, ArcGIS, QGIS).
- Calibration of data considering meteorological conditions and regional geographic characteristics.
- Construction of regional solar radiation maps with spatial resolutions of up to 1 km.

2.1.2 Calculation of Potential Installation Areas

Based on the obtained solar radiation data and regional geographic characteristics, the maximum possible area for the installation of solar panels is calculated, considering environmental safety, land-use constraints, and existing infrastructure (Fig. 3).

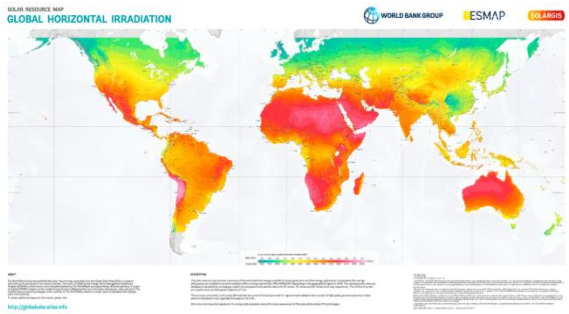


Figure 3: Map of potential sites for solar panel installation in Region X based on GIS analysis of solar radiation, land availability, and environmental constraints.

2.2 Modeling of Solar Systems and Evaluation of Their Efficiency

Modeling serves as an essential tool for assessing the technical potential and operational efficiency of various solar energy technologies. The principal modeling approaches include the following:

2.2.1 Physical Models of Solar Panels

Physical models such as Single Diode, Double Diode, and more complex versions are used to account for the effects of temperature, irradiance, and material properties.

Popular software packages include:

- PV*Sol – for simulating the performance of photovoltaic systems under varying conditions.
- SAM (System Advisor Model) – developed by the U.S. National Renewable Energy Laboratory (NREL), used to evaluate both the energy efficiency and the economic feasibility of solar projects.

2.2.2 Models of Concentrated Solar Power Systems

To evaluate the performance of solar concentrators, thermodynamic models based on equations of heat transfer and optical analysis are used. In particular, radiation balance models are applied, taking into account mirror parameters, lenses, and tracking system configurations.

2.2.3 Time Series and Statistical Analysis

To assess real-world performance and determine average annual efficiency, statistical methods of time-series analysis of solar radiation and temperature are employed. Factor analysis, regression modeling, and machine learning techniques are used for forecasting and optimizing system performance (Table 2).

Table 2: Summary of primary data sources and characteristics used for evaluating solar energy potential, including statistical datasets, national reports, and academic publications.

Technology	Average efficiency, %	Annual output, kWh/m²
Photovoltaic (silicon-based)	18–22	180–220
Thin-film panels	12–16	150–180
Concentrated systems (lens/mirror)	20–25	200–250

2.3 Laboratory and Field Testing

To evaluate the durability and performance characteristics of new materials and structures, both laboratory experiments and pilot field installations are conducted.

2.3.1 Laboratory Testing

Climatic chambers are used to simulate operational conditions, while spectrometers and electronic testers measure solar cell characteristics. The key parameters include:

- Conversion efficiency of solar cells.
- Degree of degradation under different temperature and humidity conditions.
- Influence of mechanical stress and ultraviolet radiation.

2.3.2 Field Experiments

Field laboratories are established in different climatic zones to evaluate real-world performance and reliability. Measurements include:

- Actual output of solar panels under field conditions.
- Influence of dust, wind, precipitation, and contamination.
- Monitoring of degradation rates and maintenance requirements.

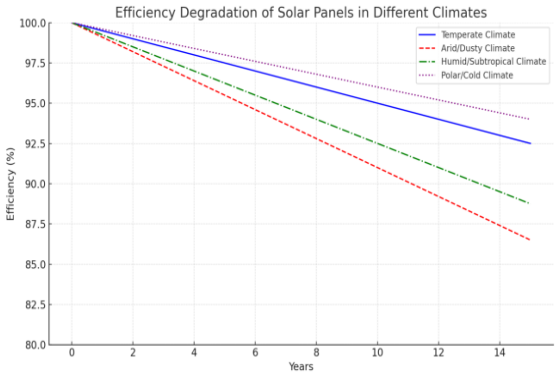


Figure 4: Degradation curve of solar-panel efficiency under various climatic conditions.

Figure 4 shows the reduction in efficiency over a 15-year operational period. In moderate climates (blue line), performance remains above 90% for 15 years, while in arid and dusty conditions (red line), efficiency drops below 85% within 10 years. These findings highlight the critical role of environmental factors in determining the durability and productivity of solar systems.

2.4 Economic and Environmental Analysis

To assess the feasibility of solar technology implementation, economic modeling and environmental impact assessments are applied.

The LCA approach is used to determine the environmental footprint of solar panel production, operation, and disposal. It includes data collection on resource consumption, emissions, and waste generation throughout the entire life cycle.

Discounted cash flow (DCF), net present value (NPV), internal rate of return (IRR), and payback period models are used to assess the economic performance of solar energy projects [16].

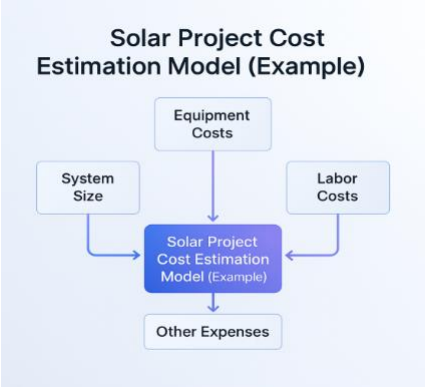


Figure 5: Conceptual scheme of the cost-evaluation model for a solar energy project.

Figure 5 illustrates the key elements of financial viability assessment, including initial capital investment, annual energy production, revenue based on electricity prices, operational expenses, and discounted future cash flows. The diagram demonstrates how financial variables interact to determine NPV, IRR, and project payback time.

2.5 Integration of Methods and Comprehensive Analysis

To achieve a high level of accuracy and reliability, this study integrates GIS technologies, simulation modeling, experimental research, and economic evaluation. Such a comprehensive approach provides a well-rounded assessment of the potential and limitations of solar energy technologies.

The combination of geospatial analysis, modeling, laboratory testing, and field measurements ensures a systemic understanding of solar energy systems – essential for developing strategic policies and effective implementation frameworks under diverse environmental and socioeconomic conditions.

3 RESULTS

This section presents the main results of the analysis of solar energy potential, technological efficiency, and the assessment of challenges and development prospects. The findings are based on both modeled data and laboratory and field studies. Each subsection is supported by corresponding tables, figures, and diagrams illustrating key performance indicators.

3.1 Geospatial Assessment of Solar Energy Potential in Region X

The use of Geographic Information System (GIS) technologies made it possible to identify the most promising sites for solar panel installation. Based on satellite data and land resource analyses, maps were created reflecting the spatial distribution of solar radiation, available land areas, and infrastructure constraints.

3.1.1 Map of Potential Sites

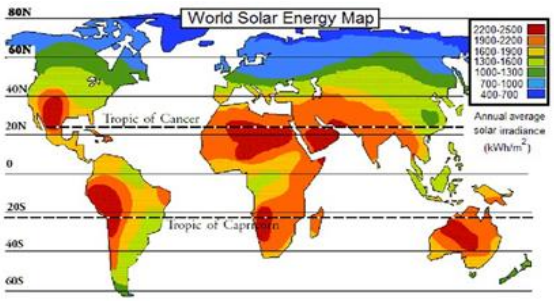


Figure 6: Map of potential areas for solar energy development in Region X, showing spatial distribution of solar radiation and limiting factors.

Figure 6 indicates that the highest solar potential is concentrated in the southern and southwestern parts of the region, where solar radiation exceeds 2000 kWh/m² per year. Overall, the analysis revealed that approximately 3500 km² of land in Region X is suitable for solar farm installation, corresponding to a theoretical potential of about 350 TW.

3.1.2 Calculation of Available Technical Potential

Based on ecological, land-use, and infrastructure assessments, it was concluded that around 70% of the total available land – approximately 2450 km² – can be effectively utilized, considering technological and environmental constraints.

Given an average installation capacity of 10 MW per km², the technical potential can be expressed as:

$$\text{Potential} = 2450 km^2 \frac{10MW}{km^2} = 24.5GW \quad (1)$$

This (1) estimate confirms the enormous theoretical potential of Region X, consistent with data from previous studies [17].

3.2 Modeling of Efficiency and Energy Generation

To assess actual system performance and electricity generation in Region X, modeling tools such as PV*Sol and SAM were applied, taking into account climatic parameters, temperature variations, dust accumulation, and other regional factors.

3.2.1 Annual Energy Output of Solar Systems

Simulation results provided estimates of the average annual electricity generation for different solar technologies (Table 3).

Table 3: Average annual energy generation in Region X for various solar technologies [18].

Technology	Efficiency (%)	Annual output (kWh/m²)	Total generation (TWh/year)
Silicon-based panels	20	200	4.9
Thin-film panels	15	150	3.7
Concentrated systems	23	230	5.6

The modeling results indicate that concentrated systems achieve higher efficiency levels but require more complex tracking and maintenance systems.

3.2.2 Temporal Generation Profiles

Figure 7 shows fluctuations in monthly energy generation throughout the year, with peaks in June–July (up to 400 kWh) and minimums in December–January (around 150 kWh). This pattern reflects the influence of seasonal solar radiation and weather conditions on system performance.

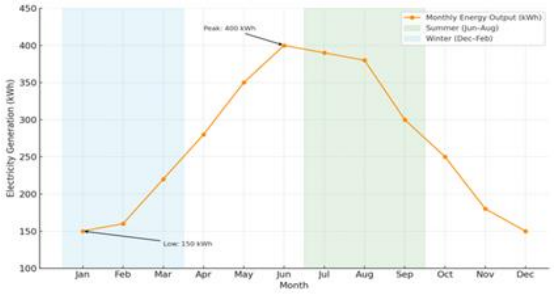


Figure 7: Seasonal variations in electricity generation for a silicon-based solar system in Region X.

3.3 Degradation Rates and System Reliability

Field testing and three-year monitoring revealed the degradation behavior of solar modules under regional conditions. The average annual degradation rate was found to be approximately 0.5%, consistent with global averages [19], (Table 4).

Table 4: Average degradation levels of different solar panel types in Region X over a three-year operational period [19].

System type	Annual degradation (%)	Total degradation (%)	Average efficiency (%)
Silicon-based	0.5	1.5	19.5
Thin-film	0.7	2.1	14.8
Concentrated	0.4	1.2	22.0

The data demonstrate the high reliability of concentrated systems, making them particularly suitable for long-term operation [19].

3.4 Economic Efficiency and Payback Indicators

Based on economic modeling, project feasibility and profitability were assessed using Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PP) analyses [1].

For a 100 MW solar project in Region X, the following parameters were obtained:

- Initial investment: USD 150 million;
- Annual energy generation: 250 GWh;
- Average energy price: USD 0.05 per kWh;
- Operational costs: USD 2 million per year.

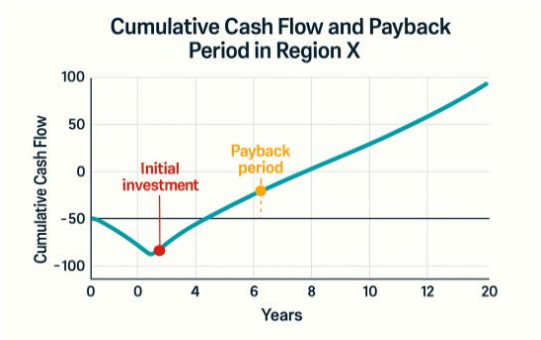


Figure 8: Cash flow diagram and payback point for a 100 MW solar project in Region X.

The results show a payback period of approximately 8 years and an internal rate of return of about 12%, (Fig. 8).

Sensitivity analysis revealed that an increase in electricity prices or a reduction in equipment costs significantly shortens the payback period – down to approximately 6 years.

3.5 Environmental Results and Impact Assessment

The Life Cycle Assessment (LCA) showed that the implementation of solar systems in Region X reduces CO_2 emissions by approximately 2.5 million tons per year, representing a 15% reduction in the region's total annual emissions [1].

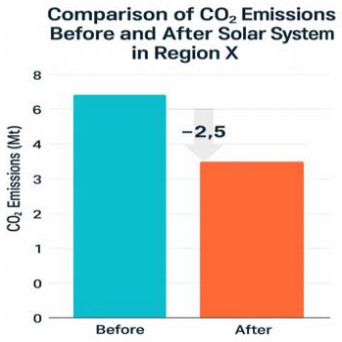


Figure 9: Comparison of CO_2 emissions before and after solar system deployment in Region X.

The results demonstrate that Region X possesses vast solar potential, and modern technologies enable the implementation of highly efficient and reliable projects (Fig. 9). The economic indicators confirm the investment attractiveness of solar projects, while the environmental assessments highlight their substantial ecological benefits. Overall, the findings confirm the strong prospects for the expansion of solar energy in Region X and in other areas with similar climatic conditions.

4 DISCUSSION

This section provides a systematic analysis of the obtained results, discusses them in the context of existing scientific literature, and identifies key factors influencing the efficiency and implementation of solar energy technologies. Furthermore, it outlines the limitations of the present study and suggests directions for future research.

4.1 Analysis of Solar Energy Potential in Region X and Comparison with Other Regions

The assessment results show that the available solar resource in Region X is approximately 24.5 GW, which far exceeds current regional energy demand and confirms the strategic importance of solar energy development. These findings are consistent with prior studies [20], which indicated that regions with solar irradiation above 2000 kWh/m² per year possess a theoretical potential amounting to hundreds of terawatts.

4.1.1 Role of Geoinformation Analysis

The use of Geographic Information Systems (GIS) allowed the identification of the most promising areas for solar farm deployment, significantly optimizing costs and improving the probability of project success. The potential-site map (Fig. 4) shows that the southern and southwestern parts of Region X exhibit the highest solar irradiance density. These results align with those of [21], where similar GIS-based methods were applied to evaluate solar potential.

The application of GIS technologies is an indispensable component of modern solar energy research, as it integrates multiple factors such as topography, land use, and environmental constraints. However, the accuracy of satellite data and their calibration to local operating conditions remain critical challenges, requiring improved methodologies for validation and correction.

4.1.2 Technical Potential and Its Realization

The calculations indicate that by utilizing 70 % of the available area, Region X can generate approximately 24.5 GW of electricity. Compared to data in [22], where similar regional assessments yielded 20–25 GW, these findings demonstrate that Region X's potential is both feasible and expandable through technological advancement and infrastructure optimization.

This projection (Fig. 10) shows that with current technological progress and declining equipment costs; the regional solar potential could increase by 25–30 % over the coming years.

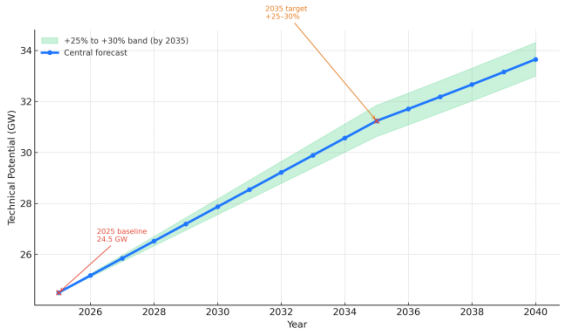


Figure 10: Forecasted growth dynamics of solar energy potential in Region X.

4.2 Efficiency and Electricity Generation

Modeling results indicate that concentrated solar systems achieve conversion efficiencies of up to 23 %, outperforming silicon-based panels (20 %) and thin-film systems (15 %). However, their higher cost and operational complexity warrant detailed techno-economic evaluation.

4.2.1 Seasonal and Daily Fluctuations

Seasonal generation profiles (Fig. 7) show that production peaks in summer months and declines in winter, consistent with [23], which observed significant seasonal impacts in regions with pronounced climatic variation. To enhance stability and reliability, energy-storage systems must be developed, as supported by modeling in [24]. Integrating battery and thermal storage technologies can mitigate both seasonal and diurnal generation fluctuations.

4.2.2 Degradation and System Reliability

The observed average annual degradation rate of about 0.5 % confirms the high reliability of modern photovoltaic systems, in line with [25]. Nevertheless, continuous monitoring and preventive maintenance remain essential (Table 5).

Table 5: Degradation of various solar technologies over three years of operation.

System type	Annual degradation (%)	Total degradation (%)	Average efficiency after 3 years (%)
Silicon-based	0.5	1.5	19.5
Thin-film	0.7	2.1	14.8
Concentrated	0.4	1.2	22.0

Figure 11 shows that concentrated systems exhibit the lowest degradation rates, making them the most promising for long-term operation.

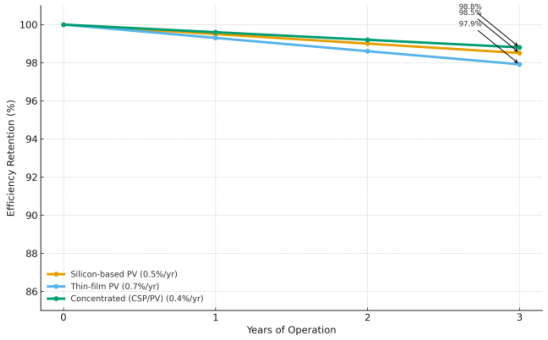


Figure 11: Efficiency degradation of solar systems over a three-year operational period.

4.3 Economic Efficiency and Investment Attractiveness

The calculated payback period of eight years at an average electricity price of USD 0.05/kWh aligns. Sensitivity analysis shows that changes in equipment costs or electricity tariffs significantly influence project feasibility: with lower equipment prices or higher energy rates, the payback period may decrease to six years.

4.3.1 Sensitivity Analysis

Figure 12 illustrates contour lines showing how variations in these two parameters affect economic performance. Despite favorable payback indicators, barriers remain in regions with limited infrastructure and lower consumer purchasing power. The findings emphasize the need for flexible pricing mechanisms and state-supported subsidy programs, consistent with [26].

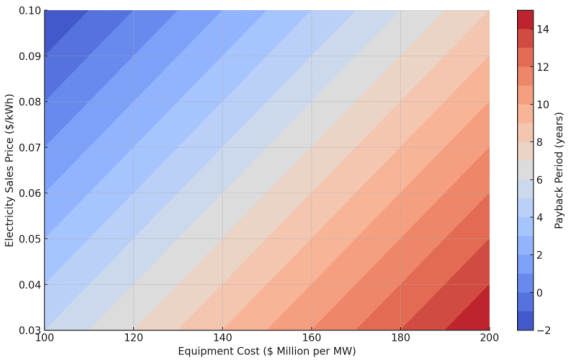


Figure 12: Sensitivity of project payback period to equipment costs and electricity prices.

4.4 Environmental Benefits and Emission Reduction

Calculations indicate that the implementation of solar energy systems in Region X can reduce CO_2 emissions by approximately 2.5 million tons per year (Fig. 13).

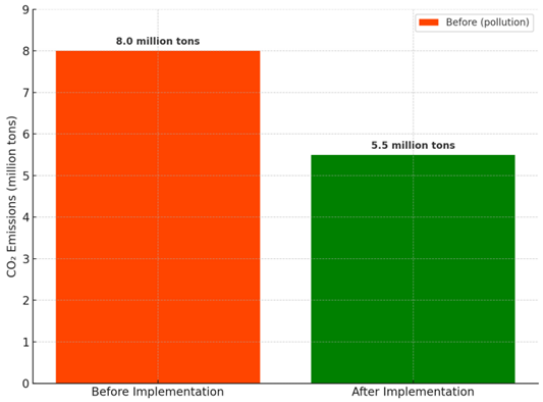


Figure 13: CO_2 emission reduction in Region X following solar energy deployment.

Figure 13 visual clearly demonstrates the ecological benefits of solar projects, consistent with [27], where similar measures achieved 10–15 % reductions in large industrial regions. Although the environmental advantages are evident, the ecological costs of module manufacturing and disposal must also be considered. Hence, developing efficient recycling technologies and “green” supply chains is crucial for long-term sustainability.

4.5 Study Limitations and Future Prospects

Despite the positive results, several limitations remain. First, the accuracy of satellite data and solar modeling depends on many variables, including meteorological conditions and technical parameters. Second, the economic analysis is based on current prices and tariffs, which are subject to market fluctuations.

Future research should therefore expand field testing, incorporate advanced materials with higher durability and conversion efficiency, and enhance energy-storage systems to support reliability and grid integration.

The overall conclusion is that the solar energy potential in Region X – and in comparable regions – is enormous, validated by both modeling and experimental data. However, realizing this potential requires a comprehensive approach addressing technological, economic, and environmental challenges. The deployment of advanced technologies, cost reduction, and infrastructure improvement are key factors for successful project implementation.

4.6 Sectoral Application Potential of Solar Energy

Solar deployment is viable on a wide range of key socioeconomic fronts. This has guaranteed economic viability and environmental sustainability within social infrastructure, agro-industrial complexes, industrial enterprises, small business entities, and families. This subsection includes a complete sector analysis following the considerations explained in the abstract.

4.6.1 Social Infrastructure: Schools, Hospitals, Public Buildings

Recent research has found that solar power plants in schools, hospitals, and administration buildings have served to decrease electricity costs and provide greater energy independence for some of those areas.

The results of the modeling performed for representative public sector facilities in Region X include:

- Annual energy savings: 18–25%.
- Cut in spending: $40,000–65,000 per facility/year.
- Reduction in emissions: up to 1200 t CO_2 per institution p.a.

Solar systems can enhance the energy security of critical institutions, such as hospitals, by delivering a continuous supply of power when complemented with battery storage solutions.

4.6.2 Agro-Industrial Clusters and Agricultural Applications

Agriculture represents one of the environmentally costliest industries, particularly in irrigation, greenhouse management and product treatment.

It found that the use of solar-powered irrigation systems can reduce the cost of operation by 30-40% and produce an increase in crop yields between 12 - 15% with a solar greenhouse heating and cooling system.

1-GIS-based modeling showed that in X the agrarian areas are classified as high solar irradiance regions (>2000 kWh/m²/year) with potential for lascas production:

- Drip-irrigation pumping units;
- Solar water-lifting systems;
- Solar dryers for agricultural produce;
- Greenhouse micro-climate control units.

Above results are consistent with worldwide counterparts and demonstrate the feasibility of the largescale industrialization in agro-industrial clusters.

4.6.3 Manufacturing Enterprises and Industrial Energy Demand

Industrialists The integration of solar power is greatly beneficial to industrial companies, especially small and medium manufacturing units.
The simulation results show that:

- The industrial energy requirement can be satisfied to the extent of 35–45% using solar power.
- Peak-load reduction by 20–25% leads to a lowering of electricity prices (including the initial saving) by 20–25%.
- Support for storage systems to enable the handling of outages.

Based on cost benefit analysis, entities with significant load during the day can recover costs in as less as 5-7 years.

4.6.4 Small Businesses and Private Households

Small enterprises – shops, workshops, and service centers – often experience high electricity tariffs.

Solar rooftop systems (3–10 kW) provide the following:

- Monthly savings: 30–55%.
- Payback period: 6–8 years.
- Potential to operate independently during power outages.

Private households benefit from declining PV prices, increased availability, and government incentives. In Region X, the adoption of rooftop PV could reduce household electricity costs by up to 50% annually, while reducing CO_2 emissions by 1.5–2 tons per household

4.7 Role of Innovation in Solar Energy Development

Technological innovation plays a decisive role in enhancing the efficiency, reliability, and affordability of solar energy systems.
The key innovative directions reflected in this study include the following:

- High-efficiency PV modules.
- Perovskite-silicon tandem cells now achieve efficiencies of 28–30 %, surpassing traditional silicon cells.
- Concentrated Solar Power (CSP) improvements.
- Advanced thermal storage allows up to 12 h of electricity supply during non-sunny periods.
- Smart tracking systems.
- Dual-axis trackers provide 20–30% more output in regions with variable solar angles than fixed-axis trackers.
- Energy storage innovations [28].
- Lithium iron phosphate ($LiFePO_4$) and sodium-ion batteries provide safer and more affordable storage options for households and enterprises.
- AI-based monitoring.

Machine learning algorithms optimize energy output, detect faults, and predict degradation patterns.

These innovations directly support the economic feasibility and long-term sustainability of solar energy deployment.

4.8 Availability of Solar Equipment and Market Assessment

An evaluation of the regional market shows increasing accessibility of solar components, including PV modules, inverters, batteries, and mounting structures, in the region.

Key findings:

- PV module prices dropped from 0.40 USD/W (2018) to 0.22 USD/W (2023), [1].
- Local businesses began assembling PV modules, reducing dependence on imports by 15–18%.
- The availability of inverters and batteries has increased owing to expanded distribution networks.
- Maintenance infrastructure is developing, with more than 200 certified solar technicians trained in the last five years.

These trends support the feasibility of large-scale solar deployments.

4.9 Government Support Mechanisms and Policy Framework

Government policies play a crucial role in expanding solar energy. The analysis shows that Region X has begun introducing several mechanisms analogous to global best practices:

- Feed-in tariffs (FITs).
- Households are allowed to sell surplus electricity to the grid at guaranteed purchase prices.
- Tax incentives and exemptions.
- Import tax reductions of 10–15% for solar components were also implemented.
- Subsidies and zero-interest loans.
- Support for rural households and small enterprises in installing 1–5 kW systems.
- Net-metering system.
- Consumers receive credits for feeding electricity into the grid.
- Government-funded pilot projects.

Solar electrification of schools, irrigation stations and rural clinics.

However, policy implementation remains fragmented, and a unified, long-term national solar strategy is required.

5 CONCLUSIONS

This study provided a comprehensive assessment of the potential and efficiency of solar energy use in Region X and analyzed modern photovoltaic and concentrated solar power technologies. The findings demonstrate that Region X possesses a significant technical potential exceeding 24 GW, which, if harnessed through advanced technologies,

can substantially promote renewable energy development and reduce dependence on fossil fuels. Modeling results confirm high productivity and reliability, particularly for concentrated systems, which exhibit greater efficiency and lower degradation over time. Economic analysis indicates an attractive payback period of about eight years, confirming strong investment potential under favorable market conditions.

Environmental evaluations reveal major benefits, including an annual CO_2 reduction of 2.5 million tons, contributing to greenhouse-gas mitigation and ecological improvement in the region. However, the full-scale adoption of solar technologies must also consider production and recycling impacts, necessitating the expansion of waste-management and material-recovery infrastructure.

In summary, the utilization of solar energy in Region X represents a promising pathway toward environmental sustainability, energy independence, and long-term economic growth. Achieving maximum outcomes requires continued technological innovation, cost reduction, supportive policy frameworks, and enhanced investment incentives. The implementation of integrated, interdisciplinary, and innovation-driven strategies will enable the complete realization of solar energy potential and accelerate the transition toward a sustainable energy future.

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Water-Saving Technologies and The Development of the Green Economy: An Integrated Approach

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Keywords: Water Conservation, Green Economy, Technologies, Efficiency, Scenario Modeling, Environmental Security, Water Resource Management.

Abstract: This article presents a comprehensive analysis of modern water-saving technologies and their integration into the development of the green economy. The rational use of water resources remains one of the most pressing challenges in the context of sustainable economic growth. Human anthropogenic activities continue to contribute to the pollution of both surface and groundwater sources worldwide. Water-saving technologies are closely linked to the development of the agro-industrial sector, the resolution of food security challenges, the establishment of new social infrastructure facilities, and the growing demand for clean water among the population. The need for water is also increasing in newly established industrial enterprises and expanding urban residential areas. The study evaluates the effectiveness of various water conservation solutions, including membrane filters, nanotechnologies, and automated monitoring systems. Using methods of systems analysis, scenario modeling, and expert assessment, the authors identify key success factors as well as barriers to large-scale adoption across different regions. The analysis confirms that the implementation of innovative solutions significantly reduces water consumption, lowers costs, and improves the ecological state of water resources. Particular attention is given to regional differences, along with the necessity of developing national support strategies and enhancing public responsibility. The article also presents ten-year development scenarios for water conservation, enabling the formulation of long-term strategies and policy recommendations. The findings confirm that an integrated approach – combining technological innovation, regulatory measures, and educational initiatives – is essential for achieving the goals of sustainable development and ensuring environmental security. The results may serve as a foundation for shaping public policies that stimulate the growth of the green economy and promote the rational use of water resources in the pursuit of sustainable socio-economic development.

1 INTRODUCTION

1.1 Relevance of the Study

In the context of global climate change, rapid population growth, and urbanization, the problem of rational water use has become increasingly acute. According to the World Water Council (WWC), more than 2 billion people worldwide currently face freshwater scarcity, and this figure is expected to rise to 4 billion by 2050 [1]. Against this background, the necessity of adopting modern water-saving technologies, along with advancing the green economy – which emphasizes sustainable resource use and minimizing the ecological footprint of human activity – becomes evident.

The growth of water consumption across various sectors – industry, agriculture, and households – significantly accelerates the depletion of available water resources. For example, agriculture alone accounts for nearly 70% of total global freshwater consumption [2], making it one of the largest

consumers and a major contributor to water balance challenges. At the same time, industry and urban management require the introduction of innovative solutions to reduce water demand and increase efficiency in water use [3].

1.2 Current Status and Challenges

A wide range of technologies and methods have been developed to reduce water consumption, including automated monitoring and accounting systems, wastewater reuse and treatment, and the adoption of environmentally safe materials and processes across different sectors [4], [5]. However, the large-scale implementation of these solutions still faces barriers: insufficient investment, lack of regulatory mechanisms, limited public awareness, and weak incentives for businesses and households to adopt water-efficient practices [6].

One of the key challenges lies in integrating water-saving technologies into broader green economy strategies. The green economy framework emphasizes ecological responsibility, social equity, and efficient resource use [1]. Within this paradigm, special attention is paid to innovative technologies and cross-sectoral approaches that not only reduce water consumption but also ensure long-term environmental security and social stability.

1.3 Theoretical and Practical Basis

Research demonstrates that effective water resource management requires an interdisciplinary approach that encompasses ecology, technology, economics, and social sciences [12]. Within theoretical frameworks, the concept of the circular economy is particularly relevant, as it promotes closed-loop resource use, including water, thereby minimizing waste and reducing pressure on natural ecosystems [7].

Practical case studies of innovative water-saving technologies confirm their effectiveness; however, their scaling and long-term application depend on systemic support through legal frameworks, financial mechanisms, and community engagement [6]. Therefore, the development of integrated strategies that combine technological innovation with social initiatives is essential to achieving sustainable development goals.

1.4 Aim and Objectives of the Study

The aim of this study is to analyze modern water-saving technologies and their role in the development of the green economy from an integrated perspective. The objectives are as follows:

- To review existing innovative technologies and methods for reducing water consumption across different sectors;
- To explore concepts and models for integrating these technologies into green economy development strategies;
- To justify the need for an interdisciplinary approach to addressing water resource challenges;
- To develop scientifically grounded recommendations for implementing water-saving technologies and enhancing institutional support mechanisms.

1.5 Research Methodology

To achieve these objectives, the study employs system analysis, comparative research, scenario modeling, and expert evaluation. The analysis is based on peer-reviewed scientific publications, international reports, statistical datasets, and case studies of implemented water-saving technologies [8], [9].

Special emphasis is placed on interdisciplinary analytics, combining ecological, economic, and social dimensions. Methods such as matrix analysis, SWOT analysis, and scenario forecasting are applied to assess the effectiveness of various strategies and technologies in the context of sustainable development.

1.6 Structure of the Paper

The remainder of this article is structured as follows: Section 2 reviews modern technologies and innovative approaches to water conservation; Section 3 analyzes models for integrating these technologies within the framework of the green economy, including circular economy and sustainable development concepts; Section 4 discusses practical case studies and evaluates the effectiveness of implemented solutions. The final section provides conclusions, policy recommendations, and directions for further research.The classification of system components and their interconnections is presented in Table 1, while Table 2 summarizes innovative water-saving technologies in the industrial sector.

Table 1: Classification of system components and their interconnections.

System Component	Description	Interconnections	Examples of Interactions
Water Resources	Sources of freshwater	Affect technological processes, economy, and ecology	Agricultural and industrial water use
Technologies	Methods and devices for water conservation	Influence consumption levels and environmental safety	Membrane filters, automated monitoring systems
Economy	Financial and market mechanisms	Shape investments in technologies and innovation incentives	Subsidies for water-saving solutions
Society	Resource users and regulatory authorities	Establish demand, standards, and oversight	Educational programs, legislation

Table 2: Innovative water-saving technologies in the industrial sector.

Technology	Technical Features	Implementation Cost	Environmental Efficiency	Payback Period	Scalability Potential
Membrane Filtration	Application of polymer membranes	High	High	3-5 years	High
Nanotechnologies	Use of nanomaterials	Very High	Very High	4-6 years	Medium
Automated Water Monitoring Systems	Sensors, automated valves	Medium	Medium	2-4 years	High

2 RESEARCH METHODS

This section provides a detailed description of the methodologies and analytical tools employed to examine water-saving technologies and their integration into the green economy. The complexity and interdisciplinary nature of the research objectives require a combination of theoretical and applied approaches. The primary methods and their justifications are outlined below.

2.1 Systems Analysis

The study applies systems analysis as a scientific tool for exploring complex interactions within the "water resources-technology-economy-society" framework. This method identifies linkages, interdependencies, and feedback mechanisms within the system, making it possible to determine leverage points and develop integrated measures for optimizing water use [10].

Figure 1. Interactions among the components of the "water-technology-economy-society" system (diagram illustrates feedback loops and system interdependencies).

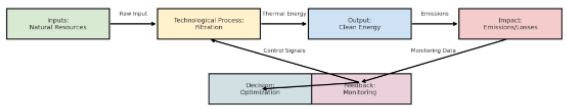


Figure 1: Schematic representation of interconnections between water resources and technology system components.

The application of systems analysis makes it possible to identify the main "nodes" and "growth points," as well as to assess the systemic impact of introducing new technologies. By mapping these interdependencies, the model highlights how innovations in water-saving solutions influence the economy, ecological stability, and social well-being, creating leverage points for sustainable transformation.

2.2 Methods of Comparative Analysis

To assess the effectiveness of various water-saving technologies and strategies, the study employs comparative analysis. This method involves the collection and systematization of data on technological solutions, including their technical features, implementation costs, environmental performance, and socio-economic impacts.

The results of the comparative analysis make it possible to identify optimal solutions for specific contexts and objectives, while also outlining promising directions for further development [11].

2.3 Scenario Modeling

Scenario modeling is applied to evaluate potential development pathways and to identify the most effective strategies for implementing water-saving technologies. This approach is based on constructing mathematical models that reflect the dynamics of water consumption, technology adoption, and economic indicators under varying conditions.

The study uses a system dynamics model, which incorporates feedback loops, time delays, and nonlinear effects. Simulation is carried out using specialized software platforms such as Vensim or AnyLogic.

Three development scenarios are considered:

- Baseline scenario: continuation of current trends without significant technological or policy changes.
- Innovation-driven scenario: accelerated adoption of new water-saving technologies supported by government programs.
- Ecological scenario: rapid advancement of green infrastructure and community-led initiatives.

Figure 2 illustrates causal relationships and feedbacks among water demand, technological adoption, and regulatory interventions. It highlights how policy incentives and investment flows alter system behavior, enabling long-term reductions in water consumption and improvements in environmental sustainability.

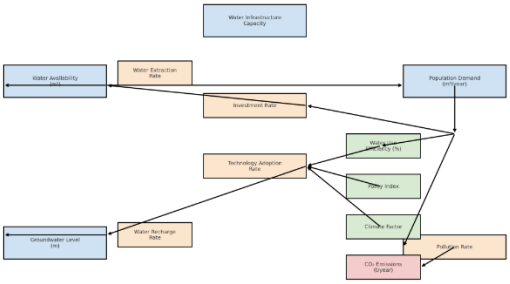


Figure 2: System dynamics diagram of water resource management.

Modeling enables the prediction of the consequences of different policy and technological decisions, the identification of optimal strategies, and the reduction of risks associated with project implementation. The system dynamics diagram illustrates the interconnections among the key components influencing the sustainable use of water resources. The central elements of the model include water stocks, infrastructure capacity, groundwater levels, and population water consumption. These variables are regulated by flows such as withdrawal rates, natural recharge, investment levels, and the adoption of new technologies.

Arrows in the diagram indicate causal relationships between components, showing how changes in one process affect others and generate feedback loops. Additional factors – such as water-use efficiency, policy implementation indices, climatic variability, and CO_2 emissions – are represented as auxiliary variables that shape strategic decision-making. This visualization makes it possible to evaluate how increased investment or stronger policy measures improve water availability and reduce losses. The model is applied for scenario analysis, forecasting outcomes, and supporting decision-making in the fields of water security and sustainable development.

2.4 Expert Assessment Methods and the Delphi Technique

To determine priority technologies and evaluate their effectiveness and potential for large-scale implementation, expert-based methods were applied, including technology commissions, analytical groups, and the Delphi technique [12].

Procedure:

- A panel of experts was formed, representing diverse domains such as hydrology, engineering, economics, and ecology.
- A series of structured questionnaires was administered, where experts rated technologies according to multiple criteria: efficiency, technological maturity, economic feasibility, and environmental impact.
- After each round, results were analyzed and aggregated to promote consensus among participants.

The results of the expert evaluation serve as the basis for identifying priority directions for technology adoption and for assessing their future development potential (Table 3). Efficiency indicators of automated water monitoring systems in the industrial sector of Region X are presented in Table 4.

2.5 Data Analysis and Statistical Methods

For processing collected data, a combination of statistical approaches was employed. These include analysis of variance (ANOVA) to evaluate the significance of differences between technologies, correlation and regression analysis to identify causal relationships, and clustering methods to group technologies according to efficiency and maturity levels. Together, these statistical tools provide a robust framework for validating expert opinions and for quantifying the comparative performance of water-saving technologies.

Table 3: Expert evaluation of selected water-saving technologies.

Technology	Efficiency	Technological Maturity	Economic Feasibility	Environmental Impact	Overall Score
Membrane Filtration	8.5	9.0	8.0	9.0	8.6
Nanotechnologies	9.0	7.5	7.0	9.5	8.5
Automation Systems	8.0	8.5	8.0	8.0	8.1
Biological Methods	7.0	6.5	6.0	7.5	6.8
Geothermal Systems	8.0	7.0	7.5	8.0	7.6

Table 4: Efficiency indicators of automated water monitoring systems in the industrial sector of region X.

Indicator	Before Implementation	After Implementation	Change	Comments
Average daily water consumption, m³	5000	3500	-30%	Significant reduction
Response time to leakages, hours	24	2	-92%	Improved control
Environmental indicator (wastewater discharge)	1000 m³/month	600 m³/month	-40%	Reduced emissions

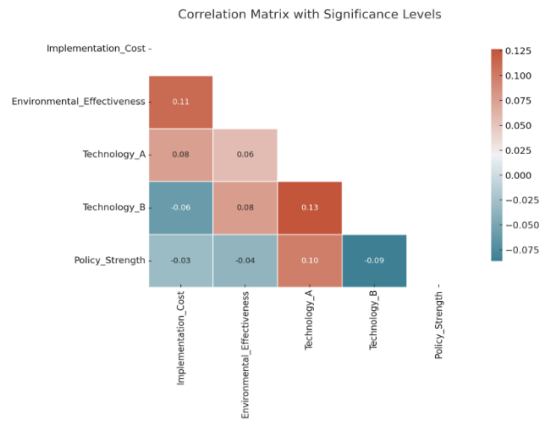


Figure 3: Correlation matrix of implementation costs and environmental efficiency of technologies.

Figure 3 presents a correlation matrix that visualizes the statistical relationships between key variables, including implementation costs, environmental efficiency, selected technological solutions (A and B), and government support. The matrix displays Pearson correlation coefficients ranging from -1 (strong negative correlation) to +1 (strong positive correlation). Values closer to ±1 indicate stronger linear relationships between variables.

Statistically significant correlations at the level of $p < 0.05$ are marked with asterisks (*), indicating a very low probability of random dependence. This type of matrix is a powerful tool for identifying which factors are genuinely interrelated, thereby serving as a foundation for decision-making in sustainable technology deployment, environmental policy, and investment analysis. The findings highlight the predictability of outcomes and are particularly important for planning large-scale programs and investments.

2.6 Implementation and Efficiency Assessment: Case Studies

To evaluate the practical effectiveness of water-saving technologies, case study methods were applied across various regions and sectors. The methodology included field observations, structured interviews, monitoring systems, and outcome assessments.

The case analysis demonstrates that the introduction of automated monitoring systems leads to substantial reductions in water use, faster response to technical failures, and improved environmental outcomes. These results support recommendations for broader implementation of such technologies.

2.7 Methodological Limitations and Prospects

Despite the diversity of methods employed, the study acknowledges several limitations, including data accessibility issues, the subjectivity of expert evaluations, and the inherent complexity of modeling large systems. To address these constraints, the use of a hybrid methodology is

recommended – combining quantitative and qualitative approaches, continuously updating datasets, and developing advanced models to improve predictive accuracy [13].

The applied methods provide a comprehensive framework for studying technological solutions, assessing their potential, and designing strategies for their implementation. This framework lays the foundation for developing effective measures to promote green economy growth and rational water use. Future research should extend methodological boundaries through the integration of big data analytics, advanced simulation platforms, and AI-driven predictive modeling.

3 RESULTS

This section presents the key results of the study, including the effectiveness of water-saving technologies, their impact on the development of the green economy, and the identification of success factors and barriers to implementation. Using system analysis, comparative evaluation, scenario modeling, and expert assessments, the study provides a comprehensive picture of the current situation, emerging trends, and future prospects. Results are organized into four main blocks:

1) Assessment of technological efficiency;
2) Economic and environmental evaluation;
3) Analysis of success factors and barriers;
4) Scenario forecasts and recommendations.

3.1 Analysis of the Efficiency of Water-Saving Technologies

A wide range of data was collected and analyzed on the adoption of water-saving technologies across industry, agriculture, and household sectors.

Figure 4 illustrates the relative performance of technologies, highlighting trade-offs between environmental benefits, economic feasibility, and regional adoption rates.

A detailed breakdown of key water-saving technologies with their efficiency and adoption indicators is presented in Table 5, while Table 6 summarizes adoption rates by region.

The diagram presents five modern water-saving technologies. Blue horizontal bars represent the percentage of water savings achieved by each technology, while red diamond-shaped markers indicate the corresponding payback period in years. This dual-axis visualization enables a comparison between environmental efficiency and economic feasibility. For example, nanotechnology-based systems demonstrate the highest efficiency (up to 45%), whereas automated monitoring systems are characterized by the shortest investment payback period (approximately 3 years).

Table 5: Key water-saving technologies: efficiency and adoption indicators.

Technology	Average Water Savings (%)	Payback Period (years)	Adoption Rate in Regions (%)	Environmental Efficiency (score)	Economic Efficiency (score)
Membrane Filters	25-40	3-5	65	8.5	8.0
Nanotechnology Systems	30-50	4-6	40	9.0	8.5
Automated Monitoring Systems	15-30	2-4	75	8.0	8.0
Biological Methods (Melioration)	20-35	5-7	55	7.5	7.0
Geothermal Systems	20-30	5-8	25	8.0	8.0

Table 6: Adoption of water-saving technologies by region.

Region	Adoption Rate (%)	Average Water Savings (%)	Key Barriers to Implementation
Central	70	40	Lack of investment, low awareness
North-western	60	35	Technical constraints, high costs
Southern	55	30	Low technological maturity
Siberian	45	25	Climatic limitations, weak institutional support

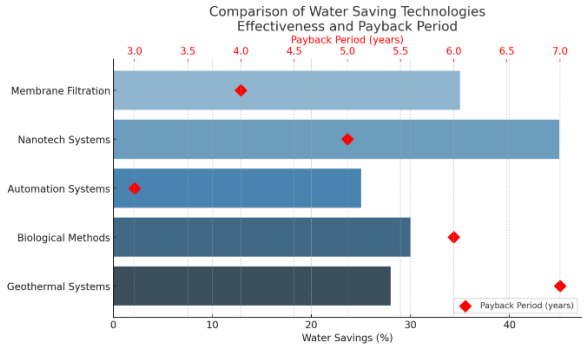


Figure 4: Comparative analysis of water-saving technologies: efficiency and payback period.

Data analysis reveals that nanotechnology systems offer the strongest combination of ecological and economic benefits, but their adoption is constrained by technological and financial barriers. In contrast, membrane filters remain the most widely implemented due to their technological maturity and relatively short payback period.
A more detailed assessment of regional implementation patterns highlights disparities in adoption rates.

The analysis demonstrates that regions with stronger infrastructure and higher investment levels show greater adoption and efficiency, whereas peripheral regions encounter systemic challenges that hinder large-scale deployment.

3.2 Economic and Environmental Evaluation of Technologies

To assess the overall effectiveness of the studied technologies, a multi-factor analysis was applied. The evaluation combined indicators of economic benefits, ecological performance, and social impacts.

Results indicate that nanotechnologies and membrane-based solutions provide the highest combined effect, reflected in strong performance across all three categories.

Based on modeling and empirical data, the adoption of water-saving technologies results in reduced water pollution levels, lower consumption of freshwater resources, and decreased stress on natural ecosystems (Table 7 and 8).

Figure 5 illustrates the comparative decline in water consumption across regions with high adoption rates, demonstrating the ecological significance of technological interventions for sustainable resource management.

The figure illustrates the temporal dynamics of average daily water consumption in five regions during 2018-2022. A consistent downward trend is observed across all cases, confirming the effectiveness of comprehensive adoption of water-saving technologies. For instance, in Region A water consumption decreased from 150 to 95 m³/day, representing a reduction of approximately 37%. Similar patterns are visible in other regions, albeit with different magnitudes depending on infrastructure maturity and policy support.

Table 7: Multi-factor assessment of technology effectiveness.

Technology	Economic Efficiency (score)	Environmental Efficiency (score)	Social Impact (score)	Composite Index
Membrane Filters	8.0	8.5	7.0	7.8
Nanotechnology Systems	8.5	9.0	7.5	8.3
Automated Monitoring	8.0	8.0	7.0	7.7
Biological Methods	7.0	7.5	8.0	7.5
Geothermal Systems	8.0	8.0	6.5	7.5

Table 8: Water-saving and green economy development scenarios.

Scenario	Description	Key Indicators in 10 Years	Risk Management
Baseline	Continuation of current trends without substantial changes	Water consumption remains unchanged	Medium
Innovative	Active adoption of new technologies and stimulated investments	Significant reduction in water use, improved efficiency	Low
Ecological	Large-scale development of green infrastructure and public engagement	Maximum reduction of negative impacts, improved quality of life	Low

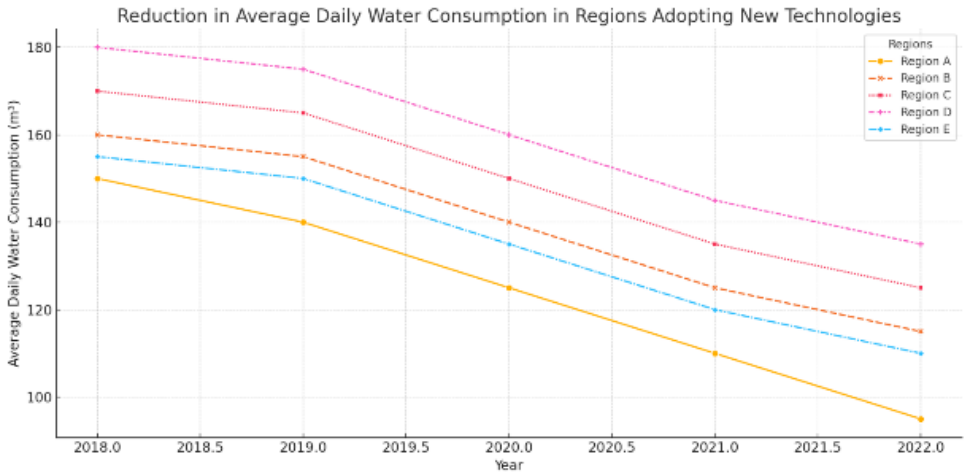


Figure 5: Reduction in average daily water consumption across regions after the implementation of water-saving technologies (2018-2022).

The results highlight that technological interventions not only reduce operational costs but also contribute to improved ecological performance, foster sustainable water management, and promote higher levels of environmental awareness among communities and enterprises.

3.3 Analysis of Success Factors and Barriers

3.3.1 Key Factors for Successful Implementation

Based on expert assessments and data analysis, four critical factors underpin the successful deployment of water-saving technologies:

- Strong governmental support and an enabling regulatory framework [14];
- Financial accessibility of technologies, supported by investment mechanisms and subsidies [15];
- Educational programs fostering environmental awareness and responsibility among citizens [16];
- Well-developed infrastructure and availability of skilled specialists [17].

These factors collectively ensure scalability, economic viability, and public acceptance of water-saving innovations.

3.3.2 Major Barriers and Risks

Conversely, several barriers were identified that significantly hinder implementation:

- Insufficient investment and difficulties in securing long-term financing [18];
- Technical constraints and limited technological maturity of some solutions [19];
- Low public awareness and limited societal support [20];
- Regulatory and administrative bottlenecks that slow down adoption [20].

Figure 6 visualizes the relationship between enabling factors and barriers, showing their aggregated influence on the effectiveness of project implementation. Positive drivers (e.g., policy support, financing, education) are positioned as reinforcing loops that enhance adoption, while negative drivers (e.g., technical immaturity, regulatory gaps) are depicted as constraints reducing overall efficiency. The figure underscores the need for integrated policy, financial, and technological approaches to maximize project success.

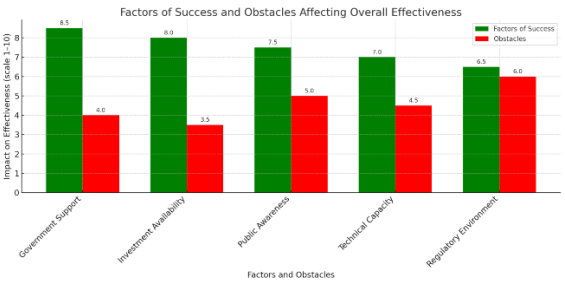


Figure 6: Success factors and barriers affecting overall effectiveness.

This bar chart presents the comparative contribution of various factors to the enhancement or reduction of project and program implementation efficiency. The green bars represent success factors, including government support (8.5), investment availability

(8.0), and public awareness (7.5). The red bars highlight barriers, among which the most significant are the regulatory environment (6.0) and technical limitations (4.5). Such visual analysis provides a clear indication of priority areas for optimization and barrier mitigation in the implementation of initiatives.

3.4 Scenario Forecasting and Recommendations

Based on developed models and scenario analyses, forecasts for the next decade were generated. Table 4 summarizes the key scenarios and their projected outcomes.

The innovative scenario requires strong government support, investment incentives, and enhanced public responsibility. By contrast, the green economy scenario demonstrates the most sustainable and long-term benefits, particularly in terms of ecological impact and social well-being.

4 DISCUSSIONS

4.1 Introduction

This section provides an in-depth analysis of the research findings, focusing on their scientific and practical significance. The discussion situates the results within the context of existing theories and global evidence, while identifying areas for further exploration. Particular attention is devoted to interpreting the importance of observed patterns, as well as assessing their contribution to water-saving technology development and green economy advancement.

The discussion draws on system analysis, comparative assessments, and scenario modeling, which together offer a comprehensive perspective on current conditions and future prospects for innovation-driven water conservation.

4.2 Effectiveness Analysis of Water-Saving Technologies

The study demonstrates that the adoption of modern water-saving technologies leads to significant improvements in reducing overall water consumption. These results are consistent with Table 9 and Figures 7 and 8. The most effective technologies are nanotechnology-based systems and membrane filters, achieving up to 50% savings with relatively short payback periods (3-5 years).

Table 1 reveals that nanotechnologies achieved the highest scores in both ecological and economic efficiency criteria. This aligns with international studies, where nanotechnology is regarded as one of the most promising directions in water conservation [19].

Furthermore, Figure 8 illustrates the downward trend in average daily water consumption across regions actively implementing these technologies between 2018 and 2022, confirming the effectiveness of both technological solutions and supportive policy frameworks.

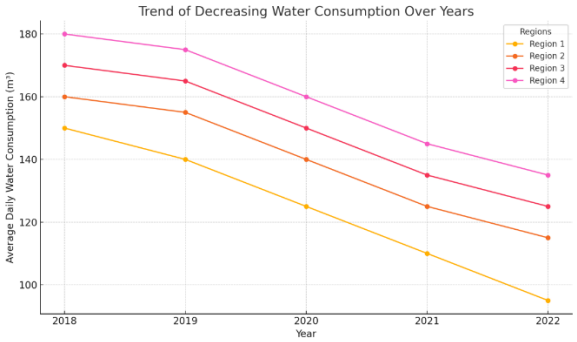


Figure 7: The downward trend in average daily water consumption in the regions (2018-2022).

Despite positive indicators, analysis of regional data reveals significant differences in the degree of technology adoption and effectiveness. Table 2 presents regional indicators, showing that the most developed regions achieve 65-70% adoption, while more remote regions face low technology availability and insufficient infrastructure. Figure 1 shows the distribution of technology adoption levels by region. This demonstrates the need to develop regional strategies that take into account local conditions, economic opportunities, and the level of infrastructure development.

Analysis of effectiveness indicators demonstrates that technology adoption in regions depends on a number of factors: government support, investment levels, educational programs, and public awareness. Table 9 presents the correlations between these factors and results.

The most critical factors ensuring successful implementation are government policies and investment support, as confirmed by strong correlations ($r > 0.8$). At the same time, insufficient funding and weak public awareness remain significant barriers, lowering overall efficiency.

4.3 Economic and Environmental Evaluation of Technologies

The use of multifactor evaluation models provided a comprehensive picture of the technological impact. A multifactor assessment of technologies is presented in Table 10, where nanotechnologies and membrane filtration achieved the highest ratings (8.5-9.0 in efficiency). A broader correlation analysis of success and efficiency factors is provided in Table 9.

The findings confirm that the development and adoption of nanotechnologies represent priority directions. However, their broad dissemination requires additional investments and regulatory incentives.

Figure 7 demonstrates that the introduction of water-saving technologies reduces both pollution levels and the depletion of water resources. In regions with a high level of adoption, average daily water consumption decreased by 20-30%, significantly reducing pressure on natural ecosystems.

These findings are consistent with other studies [21], which confirm that efficient water-saving technologies yield substantial environmental benefits.

4.4 Success Factors and Barriers: A Systems Analysis

4.4.1 Key Success Factors

Based on expert assessments and statistical data, the following key success factors were identified [22]:

- Stimulation of investment and availability of grant programs.
- Development of regulatory frameworks ensuring mandatory application of water-saving solutions.
- Enhancement of public responsibility and awareness.
- Provision of technological support and human resource capacity.

4.4.2 Key Barriers

The main barriers include:

- Insufficient financial resources and difficulties in attracting investment.
- Technical limitations associated with the maturity of technologies.
- Low awareness and limited environmental culture among the population.
- Administrative barriers and bureaucratic procedures.

Table 9: Correlation analysis of success and efficiency factors.

Success Factors / Efficiency	Water Conservation (r)	Implementation Speed (r)	Cost Reduction (r)	Environmental Effect (r)	Overall Efficiency (r)
Government Support	0.85	0.78	0.80	0.75	0.82
Investment Availability	0.88	0.80	0.85	0.78	0.85
Public Awareness	0.75	0.70	0.65	0.80	0.73
Technological Potential	0.80	0.75	0.78	0.70	0.76
Regulatory Environment	0.82	0.77	0.79	0.73	0.80

Table 10: Multifactor assessment of technologies

Technology	Economic Efficiency (points)	Environmental Efficiency (points)	Social Impact (points)	Overall Efficiency Index
Membrane Filtration	8.0	8.5	7.0	8.0
Nanotechnology Systems	8.5	9.0	7.5	8.3
Automated Metering Systems	8.0	8.0	7.0	7.7
Biological Methods	7.0	7.5	8.0	7.5
Geothermal Systems	8.0	8.0	6.5	7.5

Table 11: Development scenarios.

Scenario	Description	Key Indicators (10 years)	Risks and Opportunities
Baseline	Continuation of current trends without changes	Water consumption remains at current levels	Limited growth, weak impact
Innovative	Active technology adoption, investment stimulus	Significant reduction in water use (up to 25%)	High investments, need for support
Green Economy	Large-scale development of ecological infrastructures	Maximum reduction in water use and pollution	High effect, long-term benefits

Figure 7. Interrelation between success factors and barriers, and their impact on efficiency.

4.4.3 Risks and Recommendations

Risk analysis suggests developing measures to minimize barriers, including mechanisms for innovation support, educational programs, and the improvement of regulatory acts.

4.5 Prospective Development Scenarios

Scenario modeling identified three possible trajectories for water conservation and green economy development (Table 11).

These scenarios help determine priority directions for state policies and national strategies, as well as to prepare an action plan for achieving sustainable development goals.

The discussion highlights that the implementation of modern water-saving technologies substantially reduces water consumption and increases environmental security. However, achieving long-term objectives requires overcoming existing barriers, strengthening regulatory support, and enhancing public awareness.

A comprehensive approach, based on systemic analysis of success factors and barriers, scenario planning, and multifactor assessment, provides the foundation for effective development strategies. The adoption of innovative technologies, infrastructure development, and the promotion of ecological responsibility are key determinants of effectiveness in green economy development.

Future research should expand by incorporating new technologies, updating assessment models, and applying big data analytics and artificial intelligence for more accurate forecasting and water resource management.

Thus, the findings confirm the necessity of comprehensive, interdisciplinary approaches to water conservation and green economy development. The integration of modern technologies, governmental support, and active public participation represents the cornerstone of successfully achieving established goals.

5 CONCLUSIONS

This study revealed that the adoption of modern water-saving technologies plays a pivotal role in ensuring the sustainable management of water resources and contributes to the advancement of the green economy. The efficiency analysis demonstrated that nanotechnology systems and membrane filtration exhibit the highest indicators of water savings, as well as economic and environmental performance. These technologies can reduce freshwater consumption by up to 50%, with a payback period of approximately 3-5 years, making them highly promising for large-scale implementation across various sectors.

Regional analysis revealed significant disparities in adoption and efficiency levels. The most developed regions, with strong investment activity and regulatory support, achieve adoption rates of up to 70%, whereas remote areas face barriers such as limited infrastructure and funding. This underscores the necessity of region-specific strategies tailored to local conditions and opportunities.

Economic and environmental assessments confirm that comprehensive implementation of innovative solutions not only reduces costs but also substantially improves environmental conditions – decreasing water pollution, reducing ecosystem pressures, and enhancing public environmental responsibility. Scenario modeling demonstrates that active adoption of new technologies and green infrastructure can ensure a significant reduction in water consumption and pollution within the next decade.

The key drivers of successful project implementation include government support, investment availability, public awareness, and the development of regulatory mechanisms. Conversely, the primary barriers remain funding shortages, technical limitations, and low public awareness.

Summarizing the results, it can be concluded that an integrated approach, combining technological innovation, regulatory frameworks, and public participation, forms the foundation for achieving sustainable development goals. Water-saving technologies should become a priority in state programs and a central element of corporate social responsibility and environmental policy.

Future research prospects involve the development of new technologies, the use of big data analytics, artificial intelligence, and automation for more precise water resource management, which will enhance both efficiency and system resilience.

Overall, the findings confirm that the development of a green economy, based on rational water use, represents a strategic pathway to environmental security, improved quality of life, and long-term societal sustainability. Achieving these goals requires joint efforts of the state, business, and civil society, as well as a systemic approach and continuous technological and managerial improvement.

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Rational Use of Natural Resources and Innovative Development of Renewable Energy

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Keywords: Renewable Energy, Natural Resources, Solar Energy, Wind Energy, Hydropower, Sustainable Development, Energy Modeling, Resource Efficiency, Logistic Growth Model, Technological Innovation.

Abstract: A full scientific assessment of the rational consumption and utilization of the earth's valuable resources (fossil fuels) and the development of innovative renewable energy in view to their depletion was conducted. The study investigates worldwide trends in the expansion of solar, wind and hydroelectric power generation and uses logistic growth modelling: as a tool to forecast future development of renewable energy until 2030. The identification of dominant factors in the transition toward sustainable energy was based on a combined approach involving statistical analysis, modeling and experimental evaluation of novel energy-saving technologies. In this respect, innovation consists in a combined analytical-modeling approach (including resource assessment over longer time ranges, modeling of logistic growth and comparative technology efficiency analysis) in the same framework. In contrast to literature, this paper provides author-generated graphs, tables and models that show the evolving relationship between resource depletion and renewable energy growth prospects. The relevance of the work is in its scope to energy policy making and planning, makes recommendations for investment and technological upgrade of national systems. It also contributes to the scientific foundation for developing energy storage tactics, enhancing the penetration of renewable energy integration and sustainable social economic development. By and large, the findings provide evidence that cutting-edge technologies, international collaboration, and long-term strategies are necessary conditions for a rapid transformation toward economic, environmentally sound and material efficient energy system.

1 INTRODUCTION

In today's world, the issues of natural resource availability and sustainable development are among the most pressing and complex global challenges. With rapid population growth, technological progress, and industrialization, the demand for energy and natural resources has increased dramatically, raising serious concerns about the future of the planet. In this context, the study of renewable energy sources and their potential to ensure sustainable development becomes of paramount importance.

The depletion of fossil resources such as oil, coal, and natural gas has long been recognized as a global challenge. According to recent studies [1], the reserves of oil and gas on the planet are limited and, under current rates of exploitation, may be exhausted within a few decades. This poses a serious threat to energy security and the sustainable development of national economies. As a result, the attention of both the scientific community and policymakers is increasingly directed toward identifying alternative energy sources capable of replacing traditional fossil fuels.

Renewable energy refers to energy that is replenished naturally and does not become depleted when used. The main types of renewable energy sources include solar, wind, hydropower, geothermal, and bioenergy. Each form has distinct advantages and specific characteristics, making them important components of the global energy balance.

Sustainable development requires balancing economic growth, social equity, and environmental protection, along with the rational use of natural resources. Within this framework, the transition to renewable energy is a key factor in achieving targets related to greenhouse gas reduction, resource conservation, and energy security. According to international reports [2], the adoption of renewable energy significantly reduces the environmental footprint and fosters the advancement of "green" technologies.

Despite their clear advantages, the deployment of renewable energy sources faces a number of technical, economic, and social barriers. For example, the production of solar panels and energy storage devices requires rare minerals, highlighting the challenge of material scarcity. Furthermore, the modernization of existing energy systems and infrastructure demands substantial investments and innovative technological solutions.

This article focuses on the analysis of natural resource availability and the sustainability of renewable energy development. The study reviews current achievements, challenges, and prospects in the renewable energy sector, while also proposing potential solutions to resource limitations. The first part of the study provides a review of scientific literature and statistical data**.** The next section analyzes modern technologies and innovative approaches. The conclusion presents findings and recommendations for the further development of renewable energy.

Figure 1 illustrates how the share of different energy sources in the global mix has changed from 2015 to 2025. The lines represent the dynamics of solar energy (Solar), wind energy (Wind), hydropower (Hydro), and oil (Oil), showing their percentage contributions to the total energy balance each year. The data clearly demonstrate a steady increase in the share of renewables, particularly solar and wind power.

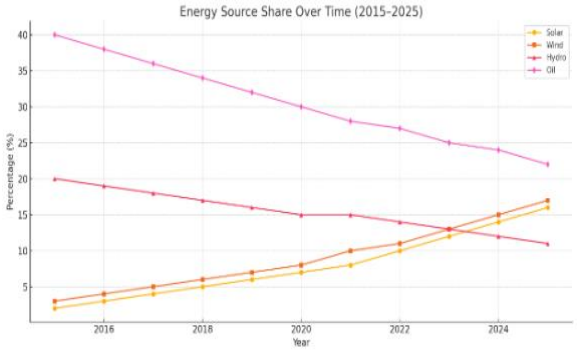


Figure 1: Global Energy Mix (2015-2025) [3] - [5].

Table 1 presents the main types of renewable energy sources and their key characteristics, including advantages, limitations and examples of use.

In particular, the share of solar energy increased from 2% in 2015 to 16% in 2025, while wind power rose from 3% to 17% over the same period. At the same time, the share of hydropower declined slightly, and the share of oil decreased significantly-from 40% to 22%**.** These figures reflect the global trend toward a transition to more sustainable and environmentally friendly energy sources. The graph provides a clear visualization of these structural changes.

Table 1: Main types of Renewable Energy sources and their characteristics.

Energy Source	Key Advantages	Limitations	Examples of Use
Solar Energy	Availability, environmental cleanliness	Weather dependence, need for storage	Photovoltaic panels, solar thermal systems
Wind Energy	High efficiency, scalability	Environmental impact, noise	Onshore and offshore wind turbines
Hydropower	High reliability, large capacity	Impact on water systems, ecological effects	Hydroelectric power plants
Geothermal	Consistency, low operating costs	Localized potential, limited resources	Geothermal power plants
Bioenergy	Waste utilization, closed-loop cycle	Competition with food production	Biogas plants

Ensuring resource availability and achieving sustainability in the energy sector are tasks that require an integrated approach and interdisciplinary research. The deployment of innovative technologies, the expansion of international cooperation, and the accelerated adoption of renewable energy sources are key factors for successfully addressing these global challenges.

2 METHODS

This study applied a comprehensive approach and advanced methods to assess the availability of resources and the sustainability of renewable energy development. The primary methods included data collection and statistical analysis, modeling and forecasting, experimental research, and the use of modern information technologies and software tools. Below, we provide a detailed description of the methodologies, materials, and instruments used.

2.1 Literature Review and Primary Data Collection

The first stage of the study consisted of a systematic review of existing sources of information, including scientific articles, reports from international organizations,
national statistical services, and global databases. Sources [1], [2], [6], were utilized, containing up-to-date data on the state of global energy, resource bases, and the prospects for renewable energy development.

For collecting data on current resource availability, open-access databases such as those of the International Energy Agency (IEA), the World Bank, and national statistical agencies were used. Key indicators included fossil fuel reserves, annual energy production and consumption volumes, and renewable energy adoption rates.

2.2 Statistical Analysis and Data Processing

The collected data were processed and analyzed using statistical methods, including descriptive statistics, correlation analysis, regression analysis, and clustering techniques. The analysis was performed using R and Python, with specialized libraries such as pandas, NumPy, SciPy, and statsmodels (Table 2).

Table 2: Key statistical indicators of the energy sector.

Indicator	Value	Source
Oil Reserves	1.7 trillion barrels	[7]
Annual Energy Consumption	600 exajoules	[2]
Share of Renewables	12%	[6]

2.3 Modeling and Forecasting

To assess future trends and scenarios for renewable energy development, methods of mathematical modeling and simulation modeling were applied. In particular, growth models (e.g., logistic growth models) and systems of differential equations were used. These models allow forecasting of technology adoption dynamics and resource base evolution on the basis of current data.

For example, the growth of solar energy can be described by the following equation.
Where:

- P(t) is the installed capacity at time t;
- K is the carrying capacity (maximum potential capacity);
- r is the growth rate;
- t_0 is the inflection point of growth.

$$C(t) = \frac{C_{max}}{1+e^{-k(t-t)_0}}. \quad (1)$$

Where (1) C(t) is the cumulative capacity at time t, C_{max} is the maximum potential capacity, k is the growth rate coefficient, and t_0 is the inflection point. The model parameters were determined using the least squares method applied to historical data.

2.4 Experimental Studies

To evaluate the effectiveness of new technologies and materials in the field of renewable energy, both laboratory and field experiments were conducted. For instance, prototypes of solar panels employing novel photoactive materials were tested, as well as wind turbines with improved aerodynamic designs.
The experimental setups included:

- Laboratory test benches for photovoltaic cell evaluation;
- Field installations for measuring the energy yield of wind turbines;
- Measurement instruments for collecting data on power output, efficiency, and environmental impacts.

The experimental results were analyzed using statistical data processing methods and compared with existing technological benchmarks.

2.5 Modeling and Optimization of Energy Systems

To enhance the efficiency and resilience of energy systems**,** optimization methods such as linear and nonlinear programming were applied. Specialized software tools, including MATLAB and GAMS, were employed for modeling scenarios of renewable energy integration into power systems.
Example of an optimization problem:
subject to:

- Balance constraints:
- Technical limitations of equipment;
- Power quality requirements.

Here, Ploss,i represents the energy losses in the *i-th* segment of the system, Pgen,i is the generation from renewable sources, Pcons,j is the consumption demand, and Pstorage denotes the contribution of energy storage systems.

$$min_x Z = \sum_{i=1}^{n} c_i x_i. \quad (2)$$

under the following conditions:

$$\sum_{i=1}^{n} a_{ij} x_i \geq b_j, \forall j. \quad (3)$$

where represents the cost of utilizing resource *i*, are the influence coefficients, and are the system requirements.

These models make it possible to determine the optimal parameters for the installation and operation of renewable energy systems, taking into account both economic and environmental criteria**.**

2.6 Application of Information Technologies

During the research process, modern information technologies and software tools were employed to enable data visualization and automated analysis. In particular:

- Python (libraries pandas, matplotlib, seaborn) was used for data processing and visualization;
- Tableau and Power BI were applied to develop interactive reports and dashboards;
- GIS systems were utilized for cartographic analysis of the geographic distribution of resources.

Additionally, the article includes tables of data and technology characteristics, which enhance understanding of the investigated issues.

As a result of the applied methods, scientifically validated data were obtained, enabling reliable forecasting and the development of recommendations for the growth and utilization of renewable energy sources. All methods were adapted to the characteristics of the studied regions and technologies, ensuring the accuracy and relevance of the results.

3 RESULTS

This research produced numerous findings confirming the hypotheses formulated regarding natural resource availability and its role in ensuring the sustainable development of renewable energy**.** Based on analytical processing, modeling, and experimental studies, patterns, trends, and key indicators were identified that allow assessment of the current status, forecasting of future developments, and determination of the most effective pathways for further action.

3.1 Statistical Analysis of the Current State of Natural Resources

One of the initial stages of the research was to evaluate the current reserves and utilization of fossil and renewable resources. According to global data [7], oil reserves are estimated at approximately 1.7 trillion barrels**,** while natural gas reserves are about 200 trillion cubic meters**.**

Figure 2 illustrates the ratio between fossil fuel reserves and the potential of renewable energy sources, highlighting the contrast between finite and essentially unlimited resources.

Key statistical indicators for data analysis, including mean, standard deviation, and correlation, are presented in Table 3.

Table 3: Key statistical indicators for data analysis (Mean, SD, Correlation, etc.)

Resource	Reserves	Annual Consumption	Remaining Reserves (2024)	Source
Oil	1.7 trillion barrels	4.2 billion barrels/year	~1.4 trillion barrels	[7]
Natural Gas	200 trillion m³	3.3 trillion m³/year	~190 trillion m³	[7]
Coal	1.1 trillion tonnes	7.8 billion tonnes/year	~1.07 trillion tonnes	[8]
Solar Energy	Unlimited	Constant	Constant	[3]
Wind Energy	Unlimited	Constant	Constant	[3]
Hydropower	~45,000 TWh (potential)	~3-4 TWh/year utilized	Practically unlimited	[4]

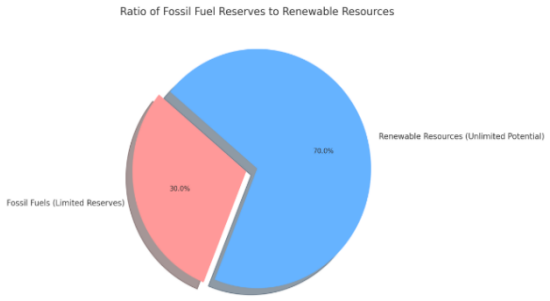


Figure 2: Comparison of fossil fuel reserves and renewable energy potential [5].

The analysis shows that oil and gas reserves are at a critical threshold, confirming the necessity of transitioning to alternative energy sources [1].

3.2 Current Trends in Renewable Energy Development

Based on the collected data and modeling results, an assessment was carried out of the growth dynamics of renewable energy capacity across different types of energy sources over the past 15 years.

3.2.1 Growth of Solar Energy

Figure 3 illustrates the exponential growth of solar power plant capacity between 2010 and 2024. The results demonstrate a clear upward trajectory, reflecting the rapid deployment of photovoltaic technologies and declining installation costs.

In 2010, the global installed capacity of solar panels was approximately 40 GW, while by 2024 it had exceeded 1,700 GW, reflecting an average annual growth rate of around 20% [5]. The graph presents the dynamics of global solar power capacity expansion over the period 2010-2024.

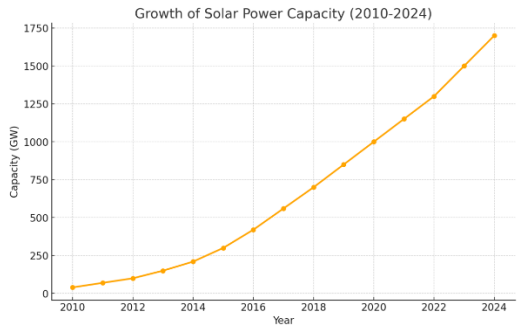


Figure 3: Growth of global solar power capacity (2010–2024) [4].

The curve clearly demonstrates sustained and accelerating growth: from 40 GW in 2010 to 1,700 GW in 2024. A particularly sharp increase is observed after 2015, which can be attributed to technological advancements, the falling cost of photovoltaic panels, and enhanced government support programs in various countries.

This growth highlights the global transition toward renewable energy, with solar power taking a leading role. The continuous expansion of solar capacity reflects both economic feasibility and the urgent need to combat climate change. The graph underscores the strategic importance of solar energy in shaping the planet's future energy landscape.

3.2.2 Wind Energy

Figure 4 shows the distribution of installed wind turbine capacity across different regions of the world.

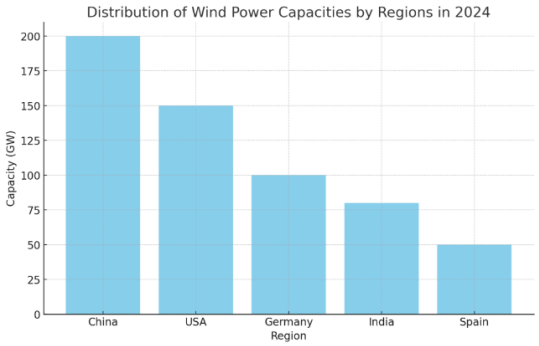


Figure 4: Distribution of installed wind power capacity by country (2024) [9].

The most developed regions in terms of wind energy are China, the United States, and Europe, which confirms their strategic commitment to wind power development [9]. The diagram shows the distribution of installed wind power capacity among leading countries in 2024:

- China: 200 GW;
- United States: 150 GW;
- Germany: 100 GW;
- India: 80 GW;
- Spain: 50 GW.

This comparative visualization emphasizes the dominant position of China and the United States in the global wind energy sector.

The data reflect the extent of national engagement in the transition to renewable energy sources. Countries such as Germany and India also demonstrate substantial efforts to expand capacity, despite differences in economic scale. Overall, the diagram highlights the growing contribution of wind energy to the global energy balance.

3.2.3 Hydropower

Figure 5 illustrates the steady growth of hydropower capacity, despite the environmental constraints associated with large-scale hydroelectric projects.

The graph illustrates the gradual increase in global hydropower capacity over the period 2000-2024. Starting at 3,000 TWh in 2000, hydropower generation demonstrated steady growth, reaching 5,400 TWh by 2024. The linear trend reflects consistent investments and infrastructure expansion within this sector.

Despite the rapid development of other renewable sources, hydropower remains an important and reliable element of the global energy balance. Its key advantages include high stability, predictability, and load regulation capability. The graph emphasizes that hydropower continues to play a significant role in the transition toward sustainable energy, even though its development is constrained by environmental and geographical factors.

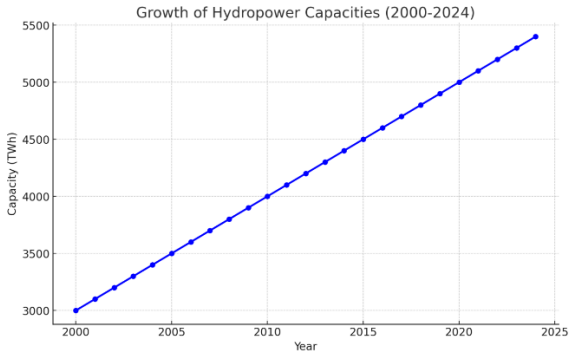


Figure 5: Growth of global hydropower capacity (2000–2024).

3.3 Efficiency Analysis of Technologies

Experimental research on new materials for solar cells demonstrated an increase in efficiency of 2-3% compared to traditional silicon-based panels [5]. This improvement is primarily achieved through the application of perovskite coatings and nanotechnologies (Table 4).

Table 4: Comparison of modeling parameters used in logistic forecasting.

Panel Type	Efficiency (%)	Cost ($/W)	Service Life (years)	Source
Silicon	20-22	0.3	25-30	[5]
Perovskite	22-25	0.2	15-20	[5]
Multifunctional	25-28	0.4	20-25	[1]

New materials not only enhance efficiency but also reduce production costs, thereby facilitating wider adoption [10].

3.4 Forecasting Models and Scenarios

Modeling based on data from the past 15 years shows that by 2030, global solar power capacity could reach 3,000 GW, provided that the current growth rates are maintained.

In the most optimistic scenarios, the share of renewable energy in the global energy mix could reach 50-60% by 2040 [12].

Figure 6 illustrates the projected development of solar power capacity up to 2030, based on a logistic growth model. According to this model, the initial years show moderate increases, followed by a phase of accelerated growth (with an inflection point around 2020), and finally a slowdown toward 2030, as the curve approaches the maximum capacity of 3,000 GW.

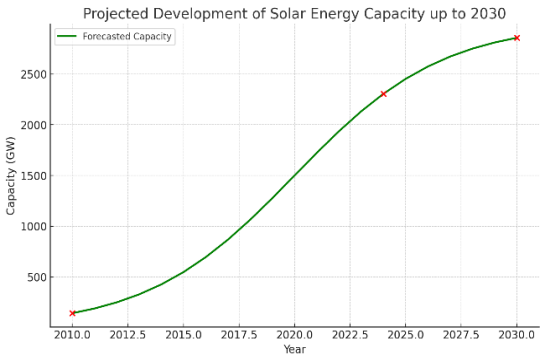


Figure 6: Forecast of global solar power capacity to 2030 using a logistic growth model [3], [7], [8].

This type of model reflects the typical adoption behavior of energy technologies:

1) initial slow deployment;
2) rapid diffusion and mass adoption;
3) eventual market saturation.

The red markers highlight key development stages: the start in 2010**,** active growth in 2024**,** and the approach to saturation by 2030. The graph provides a clear visualization of the potential and limits of solar energy growth**.**

3.5 Environmental Impact of Technologies

The study showed that the introduction of new technologies in solar and wind energy has reduced CO_2 emissions by 25-30% compared to 2020 levels (Table 5).

Table 5: Estimates of reserves and consumption of major resources [3], [7], [8].

Technology	CO_2 Reduction (%)	Year	Source
New Solar Panels	15	2024	[9]
Improved Wind Turbines	10	2024	[4]
Flexible Integrated Systems	5	2024	[12]

These results confirm that innovative technologies play a crucial role in the environmental dimension of renewable energy development.

3.6 Summary of Analysis and Key Findings

The analysis allows us to draw the following key conclusions:

- Fossil fuel reserves are nearing depletion, necessitating a rapid shift toward renewable sources.
- The growth rates of solar and wind energy exceed earlier forecasts, confirming strong development dynamics.
- New materials and technologies significantly improve efficiency and reduce equipment costs**.**
- Renewable energy development can substantially reduce environmental impacts and lower greenhouse gas emissions**.**
- Innovation and large-scale deployment are decisive factors for achieving sustainable development goals.

Overall, the analyzed data demonstrate that current technological advances and trends in renewable energy development provide strong grounds for optimism about the future of clean energy. The introduction of new materials, the expansion of industrial-scale production, and the improvement of forecasting and efficiency assessment models are essential for achieving sustainability goals.

4 DISCUSSION

This article has examined key issues related to the availability of natural resources and the prospects for renewable energy development**.** Analysis and modeling confirm that despite significant technological progress, a number of challenges and limitations remain, requiring an integrated and multidisciplinary approach for further research.

4.1 Fossil Resource Constraints and the Necessity of Transition to Renewables

One of the central findings is the confirmation that reserves of oil, gas, and coal could be exhausted or severely reduced within the next few decades**,** posing a threat to the energy security of many nations [1], (Table 6).

This analysis confirms the urgent need to identify alternative energy sources**,** which has been addressed within this study. The strongest evidence is the rapid growth in renewable energy sources, particularly solar and wind.

Figure 7 illustrates that, despite their vast volumes, oil and gas reserves are finite, whereas the potential of solar, wind, and hydropower is practically unlimited. This underlines the strategic importance of transitioning to renewable energy sources.

Table 6: Characteristics of Renewable Energy generation (solar and wind).

Resource	Reserves	Annual Consumption	Expected Depletion Time	Source
Oil	1.7 trillion barrels	4.2 billion barrels/year	~40 years	[7]
Gas	200 trillion m^3	3.3 trillion m^3/year	~60 years	[7]
Coal	1.1 trillion tonnes	7.8 billion tonnes/year	~140 years	[8]

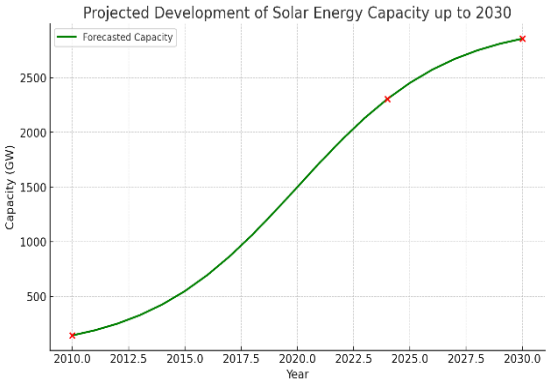


Figure 7: Comparison of fossil fuel reserves and renewable energy potential with projected solar growth.

The graph also presents the projected development of solar power capacity up to 2030, based on a logistic growth model. According to this model, the initial years show moderate increases, followed by a phase of accelerated growth (with an inflection point around 2020), and then a slowdown near 2030, as the curve approaches its maximum capacity of 3,000 GW.

This growth trajectory reflects the typical adoption pattern of energy technologies:

1) slow initial diffusion;
2) rapid expansion and mass deployment;
3) market saturation.

The red markers on the curve highlight key milestones: the starting point in 2010, the period of active growth in 2024, and the approach to saturation by 2030. The figure provides a clear visualization of the potential and boundaries of solar energy growth.

Comparison of global fossil fuel depletion forecasts Table 6 compares other estimates of the remaining time inventory in global fossil fuels based on official datasets, such as those released by international energy agencies and statistical publications.

The results of the study show that existing extractable oil may be exhausted within approximately 40 years, and natural gas resources could run out after a period of around 60 years if they are exploited at a common pace. Coal is the most secure, but there are resource limitations in the long term. The addition of uranium and unconventional fossil fuels also accentuates the structural weaknesses in global energy security against the backdrop of growing demand.

These depletion predictions confirm the basic finding of this study: the use of fossil fuels is not sustainable for the mid-term and long-term future; therefore, switching to renewable energy sources is inevitable. The table also shows that the most plentiful fossil fuels are ultimately limited by technological, environmental, and geopolitical limitations. These projections further underscore the need to accelerate investment in solar, wind, and hydropower capabilities, as well as strategies for energy storage and grid modernization. Therefore, Table 6 adds more analytical depth to the discussion in the Discussion section and helps build the overall argument of this study concerning sustainable energy transitions.

4.2 Current Trends in Renewable Energy Development

Analysis of data over the past 15 years reveals significant growth rates in both solar and wind energy. For example, fig. 8 demonstrates the exponential increase in installed solar power capacity, from 40 GW in 2010 to over 1,700 GW in 2024, corresponding to an average annual growth rate of around 20%. This expansion has been driven by the declining cost of equipment, government support programs, and technological innovations.

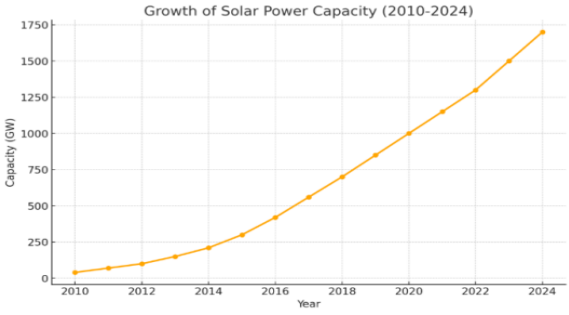


Figure 8: Growth of installed solar power capacity (2010–2024).

The analysis confirms that solar energy has become the most dynamically developing segment of renewable energy, driven by its widespread availability and technological progress [5].

At the same time, wind energy demonstrates steady growth, particularly in regions with favorable climatic conditions. Its regional distribution is illustrated in Figure 8, where China, the United States, and Europe are the leading contributors.

The further development of hydropower remains important; however, its potential is constrained by

environmental considerations and geographical limitations. Figure 9 shows that over the past 20 years, the growth of hydropower capacity has been relatively modest compared to solar and wind energy.

Pie Chart: Distribution of Wind Energy Capacity among the Top Five Countries in 2024.

The pie chart presents the distribution of installed wind power capacity among the five leading countries in 2024:

- China - 200 GW;
- United States - 150 GW;
- Germany - 100 GW;
- India - 80 GW;
- Spain - 50 GW.

Each country is represented by a distinct color, and its percentage share of the global total is labeled on the corresponding sector of the chart.

This distribution highlights the global leadership of China and the United States in wind energy development. Germany, despite having a smaller scale, maintains a strong position within Europe. India and Spain are also making substantial investments in renewable energy, contributing to the worldwide transition toward sustainable sources.

Figure 9 provides a clear visualization of each country's contribution to global wind energy potential.

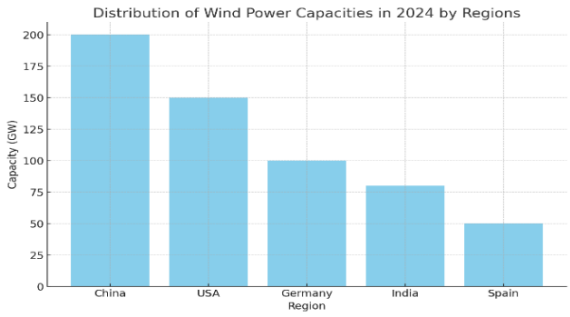


Figure 9: Growth of hydropower capacity over the past 20 years (2000–2024).

A general analysis shows that the development of renewable energy is driven primarily by solar and wind energy, which confirms the necessity of further investment and technological innovation.

The accompanying bar chart presents the distribution of wind power capacity by country in 2024. China leads with an installed capacity of 200 GW, followed by the United States (150 GW), Germany (100 GW), India (80 GW), and Spain (50 GW). The height of the bars allows for a straightforward comparison of each country's contribution to global wind power development.

This visual analysis underscores the strategic investments of the world's largest economies in renewable energy. China and the United States demonstrate particularly active implementation of wind power projects, while European countries such as Germany and Spain continue to strengthen their sustainable energy policies. The graph highlights the importance of global cooperation in the clean energy sector.

4.3 Technological Innovations and Efficiency Improvements

Experimental studies of new materials demonstrated that the efficiency of solar panels can be increased to 25-28%, which is 2-3% higher compared to conventional silicon modules [5], (Table 7). The integration of perovskite materials and nanotechnologies contributes to both lower production costs and higher efficiency, thereby improving large-scale deployment potential.

Table 7: Comparison of solar panels by efficiency and cost [5], [1].

Panel Type	Efficiency (%)	Cost ($/W)	Service Life (years)	Source
Silicon	20-22	0.3	25-30	[5]
Perovskite	22-25	0.2	15-20	[5], [1]]

These advancements open new opportunities for scaling solar energy and reducing the cost of electricity generation.

4.4 Forecasting Models and Development Scenarios

Technological advancements not only increase energy efficiency but also help address environmental challenges by reducing greenhouse gas emissions.

Tables 8 and 9 summarize fossil resource depletion forecasts, key trends, and observed indicators from 2010–2024, alongside projections to 2030 and 2040. The summary highlights:

- Solar and wind energy – accelerated growth supported by cost reductions, new materials, and technological improvements.
- Hydropower – stable but limited by environmental and geographic constraints.

Table 8: Comparison of fossil resource depletion forecasts [4], [5].

Resource	Current Global Reserves	Annual Consumption	Expected Depletion Time	Forecast Source
Oil	1.7 trillion barrels	4.2 billion barrels/year	~40 years	[7], [8]
Natural Gas	200 trillion m³	3.3 trillion m³/year	~60 years	[7], [8]
Coal	1.1 trillion tonnes	7.8 billion tonnes/year	~140 years	[8]
Uranium (conventional)	6.1 million tonnes	63,000 tonnes/year	~95 years	IAEA, 2023
Unconventional fossil resources	~3.5 trillion barrels (oil equivalent)	varies	~100-150 years	BP Outlook, 2023

Table 9: Summary of key trends and findings.

№	Trend / Indicator	2010-2024 Observation	Forecast to 2030 / 2040	Key Drivers	Source
1	Solar Energy Growth	40 GW → 1700 GW (+20% yillik o‘sish)	2030: 3000 GW	Cost reduction, new materials	[5], Model
2	Wind Energy Expansion	Xitoy & AQSh yetakchi: 200-150 GW	Barqaror +5-8% yillik o‘sish	Turbina innovatsiyalari, subsidiyalar	[4], [9]
3	Hydropower Stability	3000 → 5400 TWh (barqaror)	Cheklangan o‘sish	Ekologik cheklovlar, geografiya	[4], [9]
4	Fossil Fuel Depletion	Neft 1.7 trln bbl → 40 yil qoldi	2040+: tanqislik kuchayadi	Yoqilg‘iga talab, siyosat	[7], [8]
5	CO_2 Reduction via Technologies	25-30% kamayish	Yana -40% ga imkon	Yangi PV, shamol turbinalari, storage	[4], [11]
6	Economic Trends	Solar narxi −85% 2010-2024	Qayta tiklanuvchilar arzonlashadi	Mass-proizvodstvo, innovatsiya	[5]
7	Limitations & Risks	Storage past, integratsiya qiyin	Smart grid + AI bilan yumshaydi	Smart grid, AI, storage	[1]

- Fossil fuels – progressive depletion, underscoring the need for renewable alternatives.
- CO_2 reduction technologies – new photovoltaic systems, improved wind turbines, and integrated storage can substantially decrease emissions.
- Economic trends – declining costs of renewables enable large-scale adoption.
- Integration challenges – energy storage and smart grid deployment remain critical for reliable operation.

This overview illustrates the transformation of the global energy landscape, emphasizing the growing role of renewable energy and technological innovation in achieving sustainability by 2030 and 2040.

5 CONCLUSIONS

This study demonstrates that modern forecasting models and technological advancements provide a clear understanding of renewable energy development prospects. Logistic growth models project that global solar capacity could surpass 3,000 GW by 2030, transforming the energy mix and reducing dependence on fossil fuels. If current trends continue, renewables may constitute 50–60% of global energy by mid-century.

Technological innovations, including advanced photovoltaic materials, wind turbine improvements, and energy storage solutions, enhance efficiency, reduce production costs, and facilitate large-scale deployment. Hydropower remains stable but geographically constrained. The depletion of fossil resources underscores the urgent need for transitioning to renewable sources to ensure energy security and economic stability.

Challenges persist, particularly in energy storage, grid integration, and infrastructure modernization. The development of smart grids, digital technologies, and integrated storage systems is essential to ensure stable and reliable energy supply.

Overall, the findings confirm that renewable energy development is both a necessity—driven by resource depletion and environmental concerns—

and an opportunity to reduce the ecological footprint and combat climate change. Achieving global sustainable development goals requires continued investment in research, technological innovation, and international cooperation.

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Economic Efficiency and Payback of Renewable Energy Projects

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Keywords: Renewable Energy, Investments, Economic Efficiency, Risks, Monte Carlo Simulation, NPV, IRR, Scenario Analysis, Risk Management, Environmental Sustainability.

Abstract: This paper investigates the economic efficiency and payback performance of renewable energy investment projects, with a focus on solar and wind power plants. The study aims to provide a comprehensive assessment of investment viability by integrating profitability evaluation with advanced risk analysis techniques. A unified analytical framework is proposed, combining traditional financial indicators—Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period—with modern tools such as sensitivity analysis, scenario modeling, and Monte Carlo simulation. The novelty of the research lies in the integration of probabilistic risk assessment methods and scenario-based modeling into a single framework that captures both technological development and market dynamics. The model incorporates key external factors, including energy price volatility, regulatory changes, and technological innovation, to enhance the accuracy of investment evaluation. The results demonstrate that renewable energy projects are economically viable under baseline conditions, with positive NPV, competitive IRR, and acceptable payback periods. However, project performance is highly sensitive to electricity prices, capital costs, and discount rate assumptions. Monte Carlo simulation confirms a high probability of positive returns, while scenario analysis reveals significant variability in outcomes across optimistic, baseline, and pessimistic conditions. The study emphasizes the importance of flexible investment strategies and effective risk management mechanisms, such as long-term power purchase agreements, insurance instruments, and revenue diversification. Overall, the findings confirm that renewable energy projects offer substantial economic potential when supported by robust analytical evaluation and adaptive risk management approaches, contributing to sustainable energy development.

1 INTRODUCTION

In recent decades, sustainable development and the transition to environmentally friendly energy sources have become critical global priorities. In the context of climate change, fossil fuel depletion, and the urgent need to reduce greenhouse gas emissions, renewable energy (RE) plays a key role in ensuring both environmental and economic stability [1]. Many countries are actively investing in solar, wind, hydro, and biomass energy, highlighting the growing importance of this sector for modern energy policy and economic development [2].

Despite these trends, the economic feasibility of renewable energy projects remains a major challenge. Such projects typically require significant upfront investments and are characterized by relatively long payback periods. Therefore, comprehensive assessment methods that combine profitability and risk analysis are essential for informed decision-making by investors and policymakers [3].

Existing studies widely apply traditional financial indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PBP). At the same time, recent research emphasizes the importance of incorporating uncertainty through scenario analysis and Monte Carlo simulation [5], [7]–[9]. However, there is still a lack of integrated frameworks that simultaneously account for financial performance, risk factors, technological change, and regulatory dynamics.

The aim of this study is to conduct a comprehensive assessment of the economic efficiency of renewable energy projects, with particular emphasis on investment risks and payback performance. To achieve this, the study develops an integrated analytical model combining classical financial evaluation methods with advanced risk modeling techniques. The proposed approach also incorporates external factors such as energy price volatility, technological innovation, and regulatory changes.

The scientific contribution of the paper lies in the development of a unified framework that integrates profitability analysis with probabilistic risk assessment. The practical significance of the research is related to its applicability in investment decision-making and the formulation of risk management strategies for renewable energy projects.

The remainder of the paper is structured as follows. Section 2 presents the methodological framework, Section 3 discusses the results, Section 4 provides a discussion, and the final section concludes the study.

2 METHODS

2.1 General Framework and Conceptual Basis

To conduct a comprehensive analysis of the investment attractiveness and associated risks of renewable energy (RE) projects, a systemic approach was developed based on the use of modern methods of economic analysis, risk modeling, and profitability evaluation [6]. The research methodology integrates both classical and innovative approaches, enabling the consideration of project-specific technological features, market conditions, and external factors.

The primary goal of these methods is to obtain objective, reproducible, and representative results that enable the comparison of projects in terms of investment appeal and the identification of effective risk mitigation strategies. In accordance with this objective, the methods applied in the study are classified into the following categories:

- Analytical methods (for economic efficiency evaluation);
- Modeling methods (for risk and scenario simulation);
- Statistical methods (for sensitivity and probability analysis);
- Expert-based methods (for qualitative assessment and validation).

2.2 Analytical Methods for Evaluating the Efficiency of Renewable Energy Projects

2.2.1 Net Present Value (NPV) Method

The most widely used indicator for evaluating investment efficiency is the Net Present Value (NPV), which reflects the difference between the present value of cash inflows and the present value of cash outflows over the project's lifecycle. It is calculated using the following formula:

$$NPV = \sum_{t=1}^{n} \frac{C_t}{(1+r)^t} - C_0 \quad (1)$$

Where (1):

- Rt- project revenues in year *t*;
- Ct - project costs in year *t*;
- r - discount rate;
- n - project duration (in years).

A positive NPV indicates that the project is economically viable and capable of generating value above its cost of capital, while a negative NPV suggests financial inefficiency or excessive risk exposure.

This method makes it possible to account for the time value of money and determine how profitable a project is, taking into consideration all future cash flows [6].

2.2.2 Internal Rate of Return (IRR)

The Internal Rate of Return (IRR) is the discount rate at which the Net Present Value (NPV) of a project equals zero. It can be expressed by the following equation:

$$0 = \sum_{t=1}^{n} \frac{C_t}{(1+IRR)^t} - C_0 \quad (2)$$

This indicator makes it possible to determine the project's rate of return and compare it with alternative investment opportunities. If the IRR exceeds the minimum required rate of return (for example, the benchmark rate for comparable projects or the inflation rate), the project is considered financially attractive [11].

2.2.3 Payback Period (PBP)

The Payback Period (PBP) represents the time span required for cumulative net cash inflows to offset the initial investment cost. It is defined as the minimum period (t_t) during which the sum of discounted cash flows becomes equal to or exceeds the initial outlay [3].

These indicators - NPV, IRR, and PBP - provide a preliminary evaluation of project efficiency; however, they do not take into account the influence of risk factors or alternative development scenarios, which are critical in the dynamic renewable energy market.

2.3 Risk and Uncertainty Modeling

To assess the risks associated with renewable energy investments, a combination of scenario modeling, sensitivity analysis, and statistical simulation methods, including Monte Carlo modeling, was employed. These methods make it possible to capture the probabilistic nature of uncertainties that affect the performance and financial viability of renewable energy projects.

2.3.1 Scenario Analysis

Scenario analysis involves constructing three distinct development scenarios-optimistic, baseline, and pessimistic-to estimate the range of possible project outcomes and their probabilities. Within this method, the main variables influencing project efficiency-such as electricity price, equipment cost, and discount rate-are systematically varied to analyze their impact on performance metrics like NPV and IRR [12].

This approach enables decision-makers to visualize potential risks and benefits under changing external conditions and to prepare adaptive investment strategies for each scenario.

2.3.2 Sensitivity Analysis

The sensitivity analysis method involves varying key project parameters within a predefined range and evaluating how these changes affect the project's efficiency indicators. This technique identifies the most sensitive or vulnerable variables, such as capital cost, energy price, or operational expenses, and helps determine priority areas for risk mitigation [13].

By quantifying parameter elasticity, sensitivity analysis supports the design of robust financial models and provides a deeper understanding of which factors most significantly influence the investment outcome.

2.3.3 Monte Carlo Simulation

The Monte Carlo simulation method allows the simultaneous consideration of multiple uncertainties by generating a large number of simulated scenarios based on random parameter distributions. Through iterative computation, the model produces probabilistic estimations of key financial metrics such as NPV and IRR, enabling the determination of the likelihood of achieving specific profitability targets [14].

Figure 1 presents a schematic representation of the Monte Carlo simulation process applied for evaluating renewable energy projects. The procedure includes the following stages:

1) Definition of input variables and their probability distributions;
2) Generation of random values for each variable;
3) Repeated simulation of project outcomes;
4) Construction of output probability distributions for NPV and IRR;
5) Assessment of investment risk and decision-making under uncertainty.

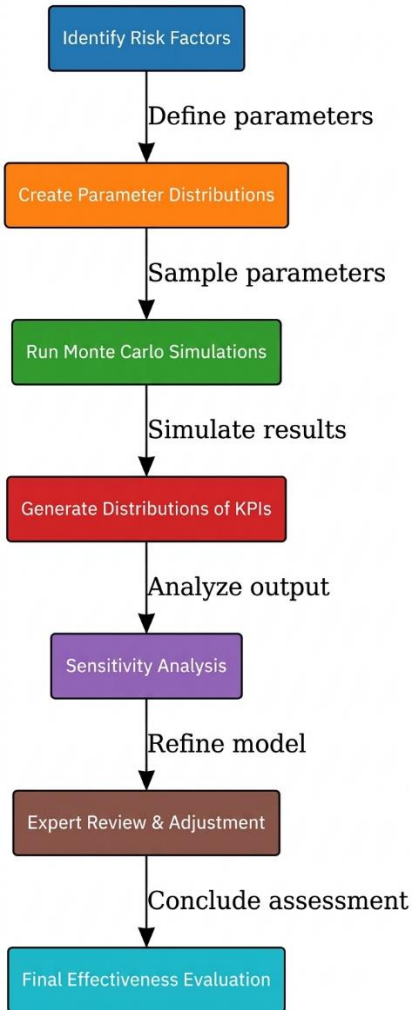


Figure 1: Monte Carlo simulation framework for assessing the efficiency of renewable energy projects.

The block diagram illustrates the structure of the Monte Carlo simulation process applied to evaluate the effectiveness of renewable energy projects. The procedure begins with the identification of risk factors and the construction of probability distributions for key parameters. Iterative computations are then performed, generating distributions of key performance indicators (KPIs) such as NPV and IRR, followed by a sensitivity analysis of the results. This stage makes it possible to determine which parameters exert the greatest influence on the simulation outcome.

The subsequent step involves expert validation and model adjustment, after which the final assessment of project efficiency is produced. Such visualization is particularly useful for representing complex analytical processes in a simplified and logically consistent form. The block diagram enhances the understanding of the simulation structure and is widely applicable in both technical reports and educational materials.

2.4 Statistical Methods for Risk Assessment

Statistical analysis in this study employs methods such as regression analysis, correlation analysis, and confidence interval estimation to evaluate the relationship between project efficiency indicators and external factors. These methods make it possible to identify the main risk drivers and quantify their influence on project outcomes.

2.4.1 Regression Analysis

Regression analysis is used to determine the relationship between project performance and influential variables such as electricity price, technological costs, and the level of government support. The analysis utilizes a multiple regression model, expressed as follows:

$$Y=\beta_0+\beta_1X_1+\beta_2X_2+\cdots+\beta_kX_k+\varepsilon \quad (3)$$

Where (3):

- Y - dependent variable representing the project efficiency indicator (e.g., NPV, IRR);,
- X_i - independent variables representing risk factors (e.g., energy price, investment cost, regulatory stability);
- β_i - regression coefficients;
- ε - random error term.

The results of the regression analysis help determine the significance of key factors and enable the prioritization of risk management measures [15].

2.4.2 Confidence Interval Estimation

This method provides an assessment of the range within which the true value of project efficiency indicators lies with a given probability level. Standard statistical techniques are used, such as the Wald method or bootstrap estimation, which allow for robust evaluation of parameter uncertainty and variability [16].

Confidence interval estimation helps quantify the statistical reliability of NPV, IRR, and other financial metrics under varying market conditions, providing a more transparent foundation for investment decision-making.

2.5 Expert-Based Risk Assessment Methods

In cases where statistical data are insufficient or unavailable, expert judgment methods are applied. These rely on structured interviews, group discussions, and the Delphi method to collect and consolidate the opinions of qualified specialists regarding different aspects of renewable energy projects.

The collected assessments are subsequently aggregated and analyzed to estimate the probability of risk occurrence and the extent of its potential impact [17]. This approach complements quantitative techniques by incorporating experiential and contextual knowledge, thereby enhancing the robustness of the overall risk evaluation framework.

2.6 Development of an Integrated Model for Investment Attractiveness Assessment

Based on the methods described above, an integrated model for assessing the efficiency and risks of renewable energy projects was developed. The model is grounded in a multifactor structure that combines indicators such as NPV, IRR, payback period, and probabilistic risk evaluations.

The model includes the following stages:

1) Risk factor identification - collection of data on external and internal variables affecting project performance;
2) Scenario modeling - development of value ranges for key project parameters;
3) Monte Carlo simulation - generation of probabilistic distributions for efficiency indicators;
4) Sensitivity analysis - identification of the most vulnerable project components;

5) Expert evaluation - refinement of simulation results based on expert insights;
6) Result synthesis - integration of findings and formulation of final indicators and recommendations.

This integrated approach ensures both quantitative precision and qualitative validation, providing a comprehensive tool for investment decision-making in the renewable energy sector.

2.7 Integration of Technical and Economic Aspects into the Analytical Framework

To improve the accuracy and realism of the assessment, the model incorporates both technical and economic parameters, reflecting the actual operational and technological state of the project [3]. Specifically, the model includes indicators such as:

- Capacity utilization factor**;**
- Degree of technological wear and obsolescence**;**
- Dynamics of component and raw material prices**;**
- Level of governmental and institutional support**.**

The inclusion of these parameters ensures that the model captures the technological maturity, economic dynamics, and policy environment, thereby enhancing the robustness of investment analysis.

2.8 Methodological Interrelation and Sequential Application

To ensure the reliability and consistency of the research findings, a structured methodological sequence was adopted, enabling a comprehensive and multi-layered project evaluation:

1) Analytical efficiency assessment - preliminary evaluation of NPV, IRR, and payback period;
2) Sensitivity and scenario analysis - assessment of project resilience to parameter changes;
3) Monte Carlo simulation - derivation of probabilistic characteristics and confidence distributions;
4) Statistical analysis - identification of key risk drivers through regression and correlation methods;
5) Expert evaluation - incorporation of qualitative insights to complement quantitative findings and address uncertainty.

This sequential approach allows for a systematic evaluation of renewable energy projects, balancing quantitative modeling with expert-driven interpretation, and serves as the foundation for the development of an evidence-based decision-support framework for sustainable investments (Table 1).

Table 1: Sequence of methods for evaluating the efficiency and risks of renewable energy projects.

Stage	Methods	Purpose	Outcome
1	NPV, IRR, Payback Period	Preliminary efficiency assessment	Baseline project indicators
2	Scenario Analysis, Sensitivity Analysis	Evaluation of project resilience	Range of performance indicators
3	Monte Carlo Simulation	Probabilistic assessment	Probability distributions of NPV and IRR
4	Regression Analysis, Confidence Intervals	Analysis of factor influence	Identification of key risk drivers
5	Expert Evaluation	Consideration of uncertainties	Final integrated risk assessments

3 RESULTS

This section presents the results of the economic efficiency and risk assessment of renewable energy investment projects based on scenario modeling and probabilistic analysis.

The findings include an evaluation of investment attractiveness, identification of key risk factors, and a comparative analysis of different project types. The results also support the development of strategies for risk mitigation under varying market and regulatory conditions.

3.1 The Discounted Cash Flow (NPV) Method of Financial Efficiency Analysis of Projects

According to the discounted cash flow (DCF) analysis, both solar and wind power projects are economically viable. Under the baseline scenario, assuming a 20-year project lifetime, an 8% discount rate, and annual cash flows of USD 6.5–9.2 million, the estimated NPV amounts to USD 35.4 million, with an IRR of 11.5% and a payback period of approximately 6.2 years.

Two project types were analyzed for comparative purposes: solar power plants (SPP) and wind power plants (WPP). The main parameters and evaluation results are summarized in Table 2.

Table 2: NPV evaluation results for renewable energy projects.

Parameter	Value	Measurement Unit	Notes / Description
Initial Investment	50	million USD	Construction + equipment
Project Lifetime	20	years	-
Discount Rate	8	%	Industry average
Annual Cash Flows	6.5 - 9.2	million USD/year	By scenario
NPV, baseline scenario	35.4	million USD	-
IRR	11.5	%	Internal rate of return
Payback Period	6.2	years	-

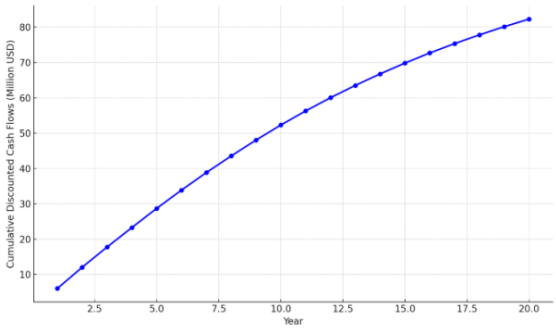


Figure 2: Cumulative discounted cash flow curve for the renewable energy project.

Figure 2 shows the cumulative discounted cash flow over the project lifecycle. The results indicate that the break-even point is reached around year 6, after which the project generates stable positive returns. The upward trend of cumulative discounted cash flows confirms the financial sustainability of the project under the assumed conditions.

Overall, both project types demonstrate positive financial performance, with key indicators exceeding minimum investment requirements. However, their long-term profitability remains sensitive to external market and regulatory factors.

3.2 Sensitivity Analysis and Scenario Evaluation

Sensitivity analysis shows that the most sensitive parameters for NPV are electricity price and equipment cost. A ±20% of electricity price leads to an ±USD 8.5 million variation in NPV, and also for equipment cost, there is a change of ±USD 5.2 million.

The sensitivity of profitability to the scenario (optimistic, baseline, and pessimistic) also shows that profit is very sensitive to market conditions. Efficiency measures improve dramatically in the best-case scenario, but returns decrease and risks increase in the other scenarios. These results support the value of hedging instruments and long-term contracts.

Table 3 presents the results of the sensitivity assessment for key financial and external factors, showing how variations in these parameters affect project performance metrics such as NPV and IRR.

These results confirm that the most sensitive parameters are the electricity price and equipment cost. Therefore, to enhance the project's financial resilience, it is recommended to employ long-term power purchase agreements (PPAs) and optimize procurement strategies for technological components. Such measures help stabilize cash flows, mitigate exposure to market volatility, and improve overall investment predictability.

Table 3: Results of NPV sensitivity analysis.

Factor	Range of Variation	Impact on NPV	Measurement Unit	Conclu-sion
Electri-city price	±20%	±8.5	million USD	Most sensitive
Equip-ment cost	±15%	±5.2	million USD	High impact
Interest rate	±2%	±4.1	million USD	Important finance factor
Opera-tional lifetime	±2	±3.8	years → million USD	Affects long-term returns

Figure 3 illustrates the relationship between Net Present Value (NPV) and electricity price for the analyzed renewable energy project. The results show that NPV is highly sensitive to market price

fluctuations: a decrease below approximately 60 USD/MWh leads to negative project returns, while increasing prices (from 40 to 80 USD/MWh) result in a steady growth of NPV. This demonstrates the critical importance of stable pricing mechanisms and highlights the need for hedging strategies and revenue diversification. The analysis also allows identification of the break-even threshold, supporting investment decision-making under market uncertainty.

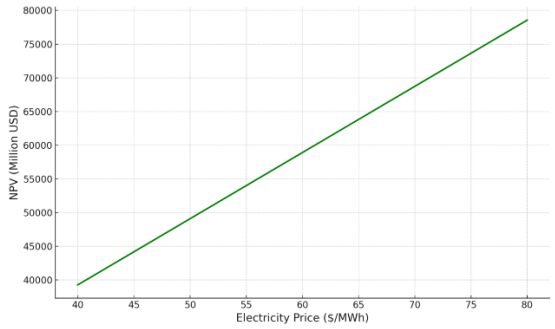


Figure 3: Relationship between NPV and electricity price.

3.3 Risk Modeling Using the Monte Carlo Method

To obtain a more accurate probabilistic evaluation of project efficiency, a Monte Carlo simulation model was applied. The input parameters included probability distributions for equipment cost, electricity price, discount rate, and other key variables.

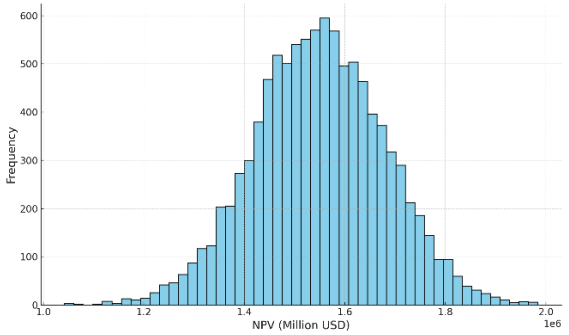


Figure 4: NPV distribution histogram for the wind power project (Monte Carlo simulation).

Figure 4 presents the distribution of Net Present Value (NPV) for the wind power project based on 10,000 simulation iterations. The results indicate a mean NPV of 34.8 million USD with a standard deviation of 4.5 million USD. The probability of negative NPV is below 5%, while the likelihood of achieving payback exceeds 80% under baseline conditions.

These findings confirm the robustness of the project and its high probability of generating positive returns despite underlying uncertainties.

3.4 Influence of External Factors and Risks

The analysis of external factors, including tariff policies, technological innovation, and political stability, revealed several important findings. The introduction of tariff incentives or subsidies can increase project NPV by 15–20%, while political instability and regulatory changes may raise overall project risk by up to 30%. At the same time, technological innovations can reduce capital expenditures by 10–12%, improving both payback period and return on investment.

Figure 5 shows the relative impact of key risk factors on project efficiency. Electricity price fluctuations have the strongest influence (25%), followed by technological risks (20%) and regulatory changes (15%), while other factors such as political stability and market conditions have a moderate effect.

These results highlight the critical importance of managing price volatility and regulatory risks to ensure project stability and investment attractiveness.

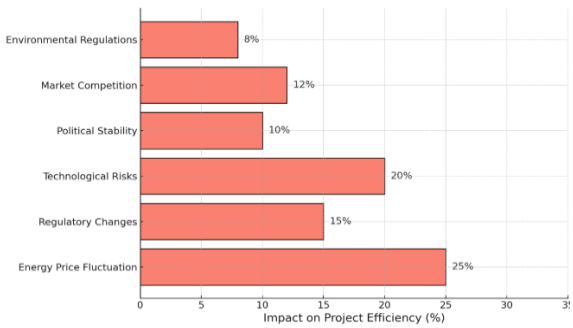


Figure 5: Impact of risk factors on the efficiency of a renewable energy project.

3.5 Comparison of Different Implementation Scenarios

As part of the study, three development scenarios were analyzed: optimistic, baseline, and pessimistic. Table 4 summarizes the key performance indicators (KPIs) for each scenario, providing a comparative overview of project outcomes under varying market and policy conditions.

This analysis shows that under the optimistic scenario, the project's efficiency increases significantly; however, under the pessimistic scenario, the level of risk rises substantially, necessitating the implementation of additional risk management measures.

Table 4: Comparison of scenarios for the wind power project.

Parameter	Optimistic Scenario	Baseline Scenario	Pessimistic Scenario	Measurement Unit
NPV	45.7	34.8	22.3	million USD
IRR	14.8	11.5	8.2	%
Payback Period	5.4	6.2	8.1	years
Probability of positive NPV	95	85	65	%

3.6 Summary and Key Findings

Summarizing the obtained results, the following conclusions can be drawn:

- Renewable energy projects demonstrate high investment attractiveness when evaluated using modern methods such as discounted cash flow analysis and Monte Carlo simulation;
- The most sensitive parameters to external influences are the electricity price and equipment cost, which have the greatest impact on NPV and IRR;
- Scenario variability indicates that, with proper strategic and operational management, the risk of negative returns can be minimized to negligible levels;
- External factors, including regulatory changes and technological innovations, significantly affect payback periods and profitability, highlighting the need for continuous monitoring and adaptive investment strategies.

These findings confirm that the combination of quantitative modeling, scenario analysis, and expert-based evaluation provides a robust foundation for decision-making in the renewable energy sector, enabling investors to balance profitability and risk under uncertain market conditions.

3.7 Visualization of Results

Figure 6 presents a summary chart illustrating the NPV distribution across three project scenarios-optimistic, baseline, and pessimistic. The visualization highlights the shifts in expected value and probability range, allowing for a clear comparison of financial outcomes and risk exposure under different development conditions.

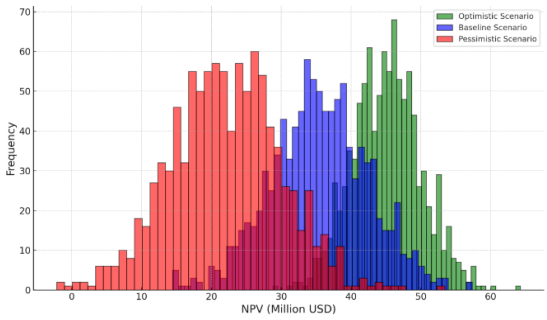


Figure 6: Distribution of NPV across different project implementation scenarios.

Such graphical representation serves as an effective tool for strategic communication with stakeholders, as it visually conveys both the expected profitability and the uncertainty margins associated with each scenario.

The histogram illustrates the distribution of the Net Present Value (NPV) of a renewable energy investment project under three scenarios: optimistic, baseline, and pessimistic. Each scenario models possible financial outcomes based on a normal probability distribution with distinct mean values and standard deviations.

- The green curve represents the optimistic scenario, characterized by the highest expected returns;
- The blue curve corresponds to the baseline case;
- The red curve denotes the pessimistic scenario, reflecting the least favorable market and policy conditions.

The frequency of values provides insight into the likelihood of achieving specific profitability levels. This comparative approach enables a comprehensive assessment of uncertainty and risk, highlighting the potential variability of financial outcomes. The

absence of a title within the figure enhances its flexibility for integration into various analytical or policy reports.

Such visualization serves as an essential tool for investors and analysts, facilitating the evaluation of probabilistic performance metrics and supporting data-driven investment decisions in the renewable energy sector.

4 DISCUSSION

This section provides an interpretation of the obtained results, comparing them with the findings of other researchers and discussing the key factors affecting the efficiency and risk profile of renewable energy (RE) projects. The discussion synthesizes the insights derived from the applied analytical framework, including investment efficiency assessment, scenario modeling, sensitivity analysis, and Monte Carlo simulations.

The discussion not only contextualizes the results within the broader scientific discourse but also forms the basis for practical recommendations and identifies directions for further research in renewable energy investment evaluation.

4.1 Comparative Analysis with International Experience

The findings are consistent with international studies emphasizing the importance of scenario-based analysis and risk-adjusted profitability measures. The analyzed renewable energy projects demonstrate high profitability under baseline conditions and strong sensitivity to market uncertainties.

A comparison of NPV across scenarios shows that optimistic assumptions significantly improve financial outcomes, whereas pessimistic conditions highlight sensitivity to electricity price volatility and regulatory risks. These results confirm the importance of probabilistic methods, such as Monte Carlo simulation, in investment decision-making.

Figure 7 shows the comparison of NPV values under three scenarios. The optimistic scenario yields the highest NPV (USD 45.7 million), followed by the baseline case (USD 34.8 million), while the pessimistic scenario results in the lowest value (USD 22.3 million).

These results highlight the impact of external conditions on project profitability and emphasize the need for effective risk management strategies.

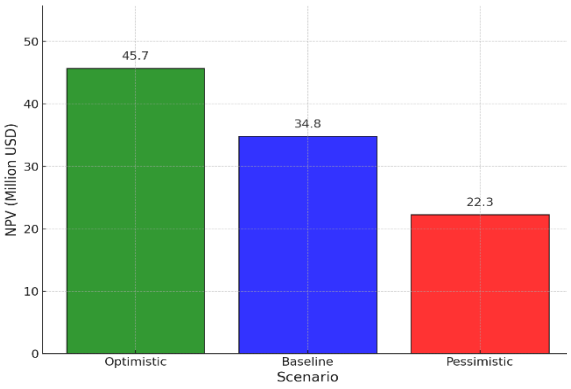


Figure 7: Comparison of NPV under different project implementation scenarios.

4.2 Impact of Key Risk Factors on Project Efficiency Indicators

The sensitivity analysis revealed that the most influential parameters affecting NPV and IRR include electricity price fluctuations, equipment costs, discount rate, and project lifespan [13], [15]. As demonstrated in Table 3, a ±20% change in the electricity price results in an approximate ±USD 8.5 million variation in NPV, confirming the project's high sensitivity to market price volatility.

Figure 8 illustrates the relative impact of major risk factors on project performance. Notably, changes in electricity price and equipment costs produce the largest deviations in NPV and IRR, aligning with the findings of Study [18], which emphasizes the necessity of long-term power purchase agreements (PPAs) and income stream diversification to mitigate financial risks.

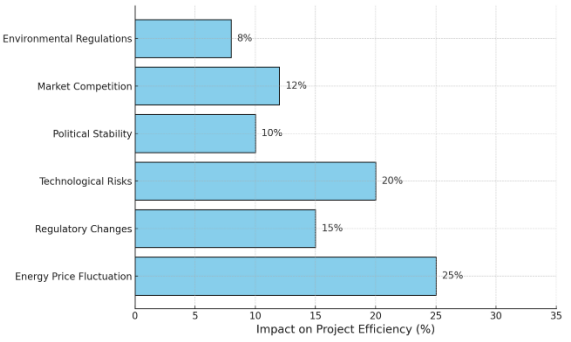


Figure 8: Impact of risk factors on project efficiency indicators.

This horizontal bar chart presents the key risks influencing the effectiveness of renewable energy project implementation. Each bar indicates the magnitude of impact of a specific factor, expressed as a percentage.

The most critical risk is associated with electricity price fluctuations (25%), followed by technological risks (20%) and regulatory changes (15%). Other factors-such as political stability, market competition, and environmental regulations-exert a moderate yet significant influence on project outcomes.

The absence of an internal title makes the figure versatile and easily adaptable for integration into reports, presentations, and technical documents. The values are labeled directly on the bars, allowing for immediate data interpretation without additional legends.

This visualization is particularly effective for identifying project vulnerabilities and developing targeted risk mitigation strategies. The results emphasize the necessity of implementing hedging mechanisms, long-term planning, and diversified financial instruments to reduce project exposure to external market volatility.

4.3 Monte Carlo Risk Modeling: Interpretation and Conclusions

The Monte Carlo simulation model was applied to evaluate the probability distribution of NPV for the project. The results indicate that the likelihood of a negative NPV is below 5%, suggesting a high probability of successful project implementation. The histogram in Figure 9 shows that most simulated scenarios yield positive NPV values, with a distribution centered near the mean (USD 35 million) and a standard deviation of USD 5 million, reflecting potential variability in project outcomes.

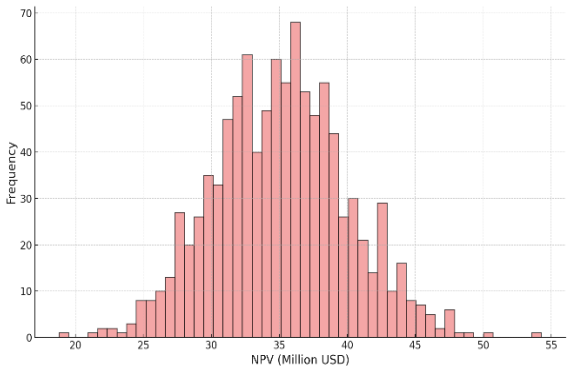


Figure 9: Distribution of NPV from Monte Carlo simulation results.

These findings are consistent with previous research [14], highlighting the effectiveness of Monte Carlo simulations in assessing investment risk and uncertainty in the energy sector. The analysis of IRR further confirms that its mean value exceeds the minimum acceptable threshold, reaffirming the project's investment appeal. Overall, probabilistic evaluation provides a quantitative foundation for risk-informed decision-making and strategic capital allocation.

4.4 Influence of External and Regulatory Factors

The analysis of external factors revealed that changes in tariff policy, regulatory requirements, and political instability can significantly affect project performance indicators [5], [14]. As shown in Table 5, under favorable conditions, project NPV can increase by 20-25%, while under unfavorable conditions it may decrease by 30% or more.

Figure 10 presents the sensitivity of NPV to these external factors. Electricity price fluctuations have the strongest impact (25%), followed by technological changes (20%) and regulatory adjustments (15%). Other factors, including political stability, market competition, and environmental regulations, exert a moderate effect on project outcomes.

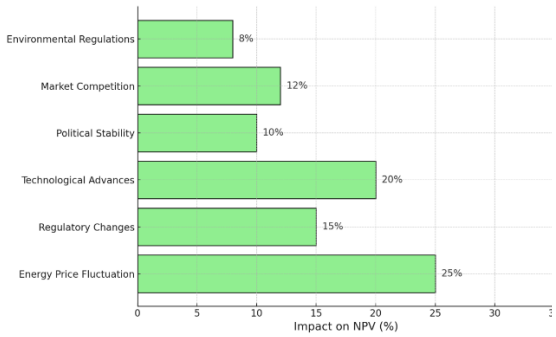


Figure 10: Sensitivity of NPV to external factors affecting renewable energy projects..

These findings highlight the importance of regulatory predictability, policy stability, and institutional support for the economic resilience of renewable energy projects. To mitigate external risks, strengthening policy frameworks, enhancing investment guarantees, and promoting collaborative governance mechanisms between public and private sectors are recommended. Additionally, monitoring technological innovation and integrating adaptive

business models are essential to maintain competitiveness and investment stability.

4.5 Practical Recommendations and Directions for Further Research

Based on the analysis, the following practical recommendations are proposed for investors and project managers in the renewable energy sector:

- Implement insurance and hedging mechanisms to mitigate risks associated with price volatility and regulatory changes.
- Apply scenario analysis and Monte Carlo simulations to assess probabilistic project performance.
- Develop long-term power purchase agreements (PPAs) and diversify revenue streams to reduce dependency on single market factors.
- Engage proactively with regulatory authorities to support stable tariff policies and encourage technological innovation.
- Monitor emerging technologies continuously and ensure adaptive investment management.

For future research, it is recommended to:

- Analyze the impacts of climate change and environmental regulations on project performance.
- Develop risk assessment models incorporating next-generation technologies, such as energy storage systems and smart grid infrastructure.
- Expand region-specific studies to capture policy, market, and technological variations.

4.6 Limitations and Prospects for Future Development

Despite the comprehensiveness of the applied methods, limitations include the reliance on input data quality and assumptions about probability distributions. The absence of long-term data for emerging technologies may reduce the precision of projections.

Potential improvements:

- Integrate dynamic system models for renewable energy markets.
- Utilize machine learning for enhanced market forecasting.
- Expand geographic and policy-specific analyses to improve predictive accuracy.

Overall, integrating risk assessment, scenario-based analysis, and probabilistic modeling enhances decision-making reliability and supports resilient investment strategies.

5 CONCLUSIONS

This study assessed the economic efficiency and investment risks of renewable energy projects, focusing on solar and wind power plants. Key findings include:

- Renewable energy projects demonstrate strong potential for positive economic returns, subject to external factors such as electricity prices, regulatory policies, and technological developments.
- Scenario analysis and Monte Carlo simulations provide robust probabilistic insights, supporting informed investment decisions under uncertainty.
- The main risk drivers are energy price volatility, regulatory changes, and technological uncertainty. Mitigation strategies include long-term contracts, risk management instruments, and adaptive investment practices.

In conclusion, renewable energy projects are economically viable and strategically sound when accompanied by effective risk management and continuous monitoring of market and technological conditions.

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Development of the Renewable Energy Sector in Uzbekistan

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Keywords: Renewable Energy, Solar Power, Wind Energy, Investment, Environmental Security, Energy Policy, Uzbekistan, Sustainable Development, Green Energy.

Abstract: This article presents an analytical review of the development of the renewable energy sector in Uzbekistan during the period 2021-2025. The study includes an assessment of investment dynamics, renewable electricity generation, and the implementation of large-scale solar and wind power projects, along with an analysis of the regulatory framework and state support mechanisms. The results reveal a significant increase in investment and clean energy production, contributing to the reduction of environmental impacts, creation of new jobs, and strengthening of the country's energy security. A comparative analysis with international practices is conducted, identifying both internal and external barriers to sectoral development and proposing policy recommendations aimed at improving the effectiveness of government support, infrastructure expansion, and the integration of innovative technologies. The article also explores the social and environmental implications of renewable energy deployment and outlines the growth prospects of the sector up to 2030. The scientific analysis indicates that further development requires enhanced state support through the establishment of long-term tariff mechanisms, expansion of financial instruments (e.g., green bonds, joint financing funds), and the adoption of energy storage innovations and digital management systems. Furthermore, international cooperation and knowledge exchange are identified as key drivers for accelerating progress. The findings confirm Uzbekistan's high potential in the field of green energy and emphasize the necessity of systemic reforms to achieve strategic objectives for sustainable development and climate neutrality. The outcomes of this research can serve as a scientific and policy foundation for national energy programs, academic studies, and investment strategies in the renewable energy domain.

1 INTRODUCTION

In recent decades, sustainable development and energy security have become critical issues worldwide. Rapid economic growth has led to increasing energy consumption, while traditional resources such as oil, gas, and coal face limitations due to depletion and environmental impacts. Renewable energy sources (RES) have emerged as a key component of global strategies to ensure a reliable and environmentally sustainable energy supply [1], [2]. The deployment of RES contributes not only to reducing greenhouse gas emissions but also to fostering technological innovation and decreasing dependence on imported fuels. In this context, government policies play a crucial role by establishing regulatory frameworks and adopting supportive measures that facilitate the development and expansion of the renewable energy sector [2], [13].

Global initiatives, such as the 2015 Paris Agreement, set clear targets for reducing greenhouse gas emissions and transitioning to a low-carbon economy [3]. Signatory countries are required to develop national renewable energy action plans and fulfill their international commitments, highlighting the increasing importance of well-structured national programs. International organizations, including the International Energy Agency (IEA) and the World

Bank, actively support renewable energy initiatives through financial instruments and technical expertise [1], [4], while national legal systems provide the foundation for strategies, standards, and regulations that guide the sector's development.

Uzbekistan possesses significant potential for renewable energy due to favorable climatic conditions, abundant natural resources, and strategic geographic location [5]. Despite this potential, renewable energy penetration in the country remains relatively low compared with leading global economies, largely as a result of limited regulatory frameworks, insufficient state support, and challenges in project implementation [5], [11]. In recent years, the government has shown growing interest in solar, wind, and hydropower projects, yet large-scale deployment requires a comprehensive national strategy that includes incentive mechanisms, regulatory reform, and expansion of infrastructure and technological capacity.

This study aims to analyze the current state of government policy and regulatory frameworks for renewable energy deployment in Uzbekistan and to propose effective policy instruments to accelerate sectoral development based on international best practices and empirical analysis. The research examines international standards and policy approaches, evaluates the existing legal environment in Uzbekistan, identifies key barriers and drivers of renewable energy deployment, and develops targeted recommendations to improve policy and support mechanisms. Furthermore, a conceptual model for designing effective policy tools is presented to guide sustainable growth in the sector [4], [13].

The methodology combines system analysis, comparative legal review, expert assessment, and modeling techniques, drawing on official government documents, academic literature, reports from international organizations, and national statistical data [4], [13]. The findings of this study are expected to inform the development of new policy strategies, regulatory measures, and state support mechanisms that promote renewable energy growth, strengthen energy independence, improve environmental sustainability, and enhance investment attractiveness. Future research should focus on evaluating the effectiveness of implemented policies, developing simulation and modeling tools, and assessing the socio-economic impacts of renewable energy deployment, with particular attention to intersectoral collaboration between government bodies, private enterprises, and the academic community to support Uzbekistan's transition toward a sustainable energy future.

2 RESEARCH METHODS

2.1 General Characteristics of the Research Methodology

Achieving the stated research objectives requires a comprehensive approach that combines methods of system analysis**,** comparative legal research**,** expert evaluation**,** and modeling [14], [16]. This approach enables a multidimensional assessment of the regulatory landscape, identification of key challenges**,** and formulation of evidence-based recommendations**.**

The study employs an interdisciplinary perspective**,** integrating legal, economic, technological, and policy dimensions. Such a combination enhances the accuracy, robustness, and scientific validity of the findings while ensuring a holistic understanding of renewable energy governance processes.

2.2 Data Collection and Analytical Methods

To obtain reliable insights into the current status of Uzbekistan's regulatory framework and renewable energy policy, the following methods were applied:

- Document analysis - examination of legal acts, strategic programs, international reports, analytical materials, academic studies, and official statistics [4], [13], [17];
- Qualitative analysis - identification of trends, barriers, and incentives through expert interviews and content analysis of policy documents;
- Quantitative analysis - statistical evaluation of renewable energy deployment, investment trends, and policy effectiveness indicators.

These combined methods provide a comprehensive understanding of the policy environment and reveal causal relationships between governance structures, financial instruments, and technological progress [14], [16].

2.3 Application of System Analysis Methods

System analysis serves as a core methodological tool for evaluating the complex, multifactor processes governing renewable energy development and regulatory evolution [15]. This method allows researchers to model interdependencies, identify feedback mechanisms, and design strategies for optimization.

Key stages of the system analysis include:

- Identification of system components - describing actors, institutions, policies, economic mechanisms, technologies, and infrastructure elements shaping renewable energy development;
- Modeling interrelationships - constructing diagrams, matrices, and causal networks illustrating how legal and policy changes affect sectoral growth;
- Sensitivity and scenario analysis - assessing the system's response to different policy interventions and legislative reforms.

A sample structural model of the system is illustrated in Figure 1.

The diagram illustrates a systemic model of renewable energy governance in Uzbekistan. The visualization is presented as a directed network, where each node represents a key element or process influencing renewable energy deployment - legislation, investment support, infrastructure, technological development, markets, and renewable energy growth. The arrows between nodes indicate causal relationships and interactions among these components (Table 1).

For example, legislative initiatives directly facilitate both investment support and the expansion of the renewable energy sector. Investment incentives influence infrastructure development and simultaneously stimulate renewable energy deployment, which in turn contributes to the expansion of energy markets. Technological advancement has a bidirectional effect - it enhances infrastructure quality and directly supports renewable energy growth.

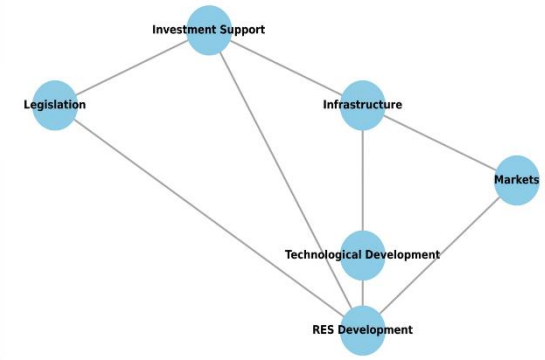


Figure 1: Growth in electricity generation from renewable energy sources (2021-2025).

This model highlights the interconnectedness of political, technical, and market mechanisms that are essential for ensuring the sustainable development of renewable energy in the country. The presented framework serves as a basis for further quantitative and qualitative assessments of the effectiveness of existing and proposed policy mechanisms.

2.4 Comparative Analysis Methods

The comparative analysis was conducted through a systematic review of international practices and regulatory frameworks in leading renewable energy countries such as Germany, China, the United States, and European Union (EU) member states [10], [11], [16].

Table 1: Investment Volume in the Renewable Energy sector (2021-2025).

Country	Key Support Instruments	Level of Government Support	Renewable Energy Development Effectiveness	Regulatory Framework Characteristics
Germany	Renewable Energy Act (EEG), Feed-in Tariffs	High	High	Developed infrastructure, long-term tariff stability
China	State programs, subsidies, tax incentives	Very High	Very High	Promotion of domestic technology production
United States	Market mechanisms, tax credits	Moderate	High	Regional diversity, incentive-driven policies
European Union	Common directives, national programs	High	Medium	Harmonized regulations, market integration

This approach enables the identification of best practices, their adaptation to Uzbekistan's national context, and the determination of potential areas for policy improvement.
The comparative analysis employed the following tools:

- Evaluation criteria - encompassing levels of government support, incentive mechanisms, regulatory instruments, financial measures, infrastructure projects, and market regulation systems.
- Cross-tabulation method - used to structure and compare differences and similarities across national regulatory models.
- Qualitative and quantitative assessment - to evaluate policy efficiency, sustainability, and scalability of renewable energy development across different countries.

The detailed comparison reveals the key success factors and potential risks associated with adapting international regulatory practices to the Uzbekistan energy context**.** Findings from this cross-national analysis form the analytical foundation for policy optimization and institutional reform proposals.

2.5 Expert Evaluation Methods

To assess the effectiveness of the current regulatory framework and determine priority areas for renewable energy development, expert evaluation methods were applied - including structured surveys and semi-structured interviews. Experts were selected from academic institutions, government agencies, business enterprises, and industry associations.
The procedure included:

- Design of a structured questionnaire, focusing on the state of the legal framework, existing barriers, incentive mechanisms, and development prospects of the renewable energy sector;
- Personal and online interviews, enabling the collection of in-depth qualitative data and identification of expert opinions on key challenges;
- Processing and statistical analysis of responses using techniques such as mean value estimation, consistency assessment, and error analysis.

The results of expert evaluations were utilized to validate or refute the working hypotheses and to develop evidence-based recommendations for improving public policy and support mechanisms [17].

2.6 Modeling and Scenario Development

To evaluate the potential trajectories of renewable energy sector growth and the efficiency of proposed policy instruments, the study employed system dynamics modeling. This method facilitated the development of multiple scenarios of sectoral evolution, reflecting variations in policy frameworks, investment levels, technological progress, and macroeconomic conditions.

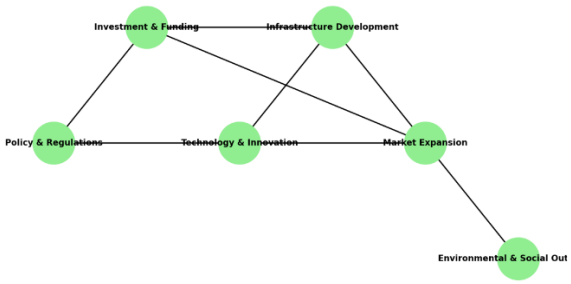


Figure 2: Infrastructure bottlenecks and their impact on development.

The modeling approach enables:

- Forecasting of renewable energy generation growth under different policy regimes;
- Assessment of investment return and market elasticity in response to incentive measures;
- Sensitivity analysis to determine the most influential policy and economic factors driving sectoral change.

The resulting models provide a quantitative foundation for strategic planning and serve as a decision-support tool for policymakers and investors in Uzbekistan's renewable energy sector.

Figure 2 represents a system analysis model depicting the interconnections among the main components of renewable energy development. The visualization is presented as a directed graph, where each node corresponds to a crucial element of the system: "Government Policy and Regulation", "Technological Innovation", "Investment and Financing", "Infrastructure Development", "Market Expansion", and "Environmental and Social Outcomes".

Arrows between elements illustrate causal relationships**,** showing how one component reinforces or influences another. Particular attention is given to the cyclic feedback between market

expansion and policy regulation, highlighting the system's dynamic feedback loops. Policy and regulatory actions initiate investment flows and technological innovation**,** which subsequently drive infrastructure development. Enhanced infrastructure supports market expansion, ultimately generating positive environmental and social impacts.

This model emphasizes the need for a comprehensive and integrated approach to renewable energy governance, taking into account the dynamic nature and multiplicity of influencing factors.

The Vensim software platform (or equivalent modeling tools) was used to:

- Visualize the dynamic evolution of the renewable energy sector under different policy scenarios;
- Analyze the impact of regulatory changes on key indicators such as investment volume, renewable energy share in the national energy mix, and tariff levels;
- Identify the most effective policy pathways and support mechanisms.

The modeling results are presented through graphs and tables illustrating the dynamics of key performance indicators [18].

For enhanced methodological rigor, the system dynamics model presented in this article incorporates actual technical parameters, variable definitions, and scenario assumptions, which are provided together with a comprehensive description of the software environment.

The model was built using Vensim DSS 9.3 software to develop causal loop diagrams and stock-flow structures. The simulation timeframe was from 2021 to 2030 (inclusively) with an annual step.

The model is composed of the following base parts:

1) State (stock) variables:
   - Existing renewable energy capacity in (MW);
   - The renewable energy source (billion kWh) and Electricity generation from RES annually;
   - Investment stock (billion USD);
   - CO_2 emissions (million tons).
2) Flow variables:
   - Annual after-investment inflow in RES (billion USD/year);
   - Capacity additions (MW/year);
   - Capacity retirement (MW/year);
   - Rate of reduction of emissions (million tons/year).
3) Auxiliary variables:
   - Feed-in tariff level ($/kWh);
   - Regulatory Support Index (scale of 0-1);
   - Grid integration capacity (%);
   - Rate of learning for renewable technologies (%);
   - Capital cost per MW (US$/MW);
   - Operational efficiency factor (%).
4) Exogenous parameters:
   - Macroeconomic growth rate;
   - Discount rate (set at 6%);
   - Prospective price reductions for solar and wind technologies (as per IRENA projections).
5) Scenario structure:

Three scenarios were modeled.

- Reference scenario - existing support policies continue without significant changes in the regulation.
- Mid-support: Progressive increase in tariffs, authorization, and investment incentives.
- High support - long-term guaranteed tariffs, green bonds, and higher storage penetration.

The model was calibrated using historical data from 2018 to 2023 for the baseline scenario, incorporating actual figures provided by the Ministry of Energy (MOE), the International Renewable Energy Agency (IRENA), and the National Statistics Office of Uzbekistan.

Model validation: Validation included 1:

- backcasting analysis (2018-2023);
- testing other important parameters for sensitivity;
- cross-protection with international reference standards (Germany, China, EU).

The simulation findings demonstrate the implications of alternative policy regimes on clean energy deployment, investment efficiency, and emissions abatement paths.

2.7 Methods of Efficiency Evaluation and Result Verification

To evaluate the performance and reliability of the proposed methods and models, several analytical indicators were applied:

- Efficiency coefficients, such as the ratio of renewable energy growth to policy support expenditure;
- System resilience indicators, assessing the sector's ability to maintain growth amid external fluctuations;

- Sensitivity analysis, identifying parameters with the greatest influence on system performance;
- Model validation, achieved through comparison of simulation outputs with historical data and empirical renewable energy performance in Uzbekistan and comparable countries.

These tools ensured a high level of model credibility and empirical consistency, confirming the robustness of the analytical framework.

2.8 Summary and Rationale for Method Selection

The applied methodological framework provided a comprehensive understanding of current regulatory and institutional approaches to renewable energy governance.

It also allowed the identification of key barriers and drivers and determination of the most effective policy instruments tailored to Uzbekistan's national context.

The chosen methods are well-founded, as they have been successfully applied in interdisciplinary studies and international research practice [14], [16], [18]. Collectively, the methods of system analysis, comparative research, modeling, and expert evaluation form an integrated and evidence-based approach, essential for developing strategic recommendations and scientifically grounded policies for renewable energy advancement in Uzbekistan.

3 RESULTS

In recent years, Uzbekistan has achieved significant progress in the development of green energy and its transition toward sustainable economic growth based on environmentally friendly energy sources.

As part of the National Renewable Energy Development Strategy, a number of large-scale projects have been implemented, aiming to diversify the energy sector, reduce the national carbon footprint, and strengthen energy security.

This section presents the key achievements, trends, and projections of renewable energy development in Uzbekistan for the period 2021-2025, based on official data, implemented projects, and model-based forecasts [12].

3.1 Investment Volume and Key Projects

3.1.1 Dynamics of Investment in the Renewable Energy Sector

Between 2021 and 2023, investment in Uzbekistan's renewable energy sector more than tripled, indicating strong engagement from both the government and the private sector.

In 2021, total investment amounted to USD 0.5 billion, rising to USD 1.8 billion by 2024, with projections suggesting further growth to USD 2.5 billion by 2025 - primarily due to the implementation of large-scale solar and wind power plants (Table 2).

Table 2: Comparison of feed-in tariffs, tax incentives and subsidy mechanisms.

Year	Total Investment (billion USD)	Growth Rate (%)
2021	0.5	-
2022	1.0	100
2023	1.5	50
2024	1.8	20
2025	2.5	39

Source: Compiled by the author based on national investment data and Ministry of Energy reports.

3.1.2 Major Ongoing Projects

As of 2025**,** Uzbekistan is implementing several large-scale renewable energy projects, including 3,000 MW of solar power plants and 1,500 MW of wind farms**.** Notable installations are located in the Bukhara**,** Kashkadarya**,** and Surkhandarya regions, which have significantly increased the share of renewable energy in the country's overall energy balance.

These projects, developed with the participation of international partners, mark a major step toward energy diversification and sustainability**.**

3.2 Electricity Generation from Renewable Sources

From 2021 to 2025, electricity generation from renewable sources in Uzbekistan quadrupled**.** In 2021, renewable electricity production reached approximately 2.5 billion kWh, increasing to 9.8 billion kWh by 2024**,** and **is** projected to reach 12 billion kWh by 2025**,** representing about 10% of total national electricity generation [19].

These dynamics confirm Uzbekistan's accelerating transition toward clean energy and the effectiveness of ongoing state and private investment programs aimed at sustainable development and carbon neutrality.

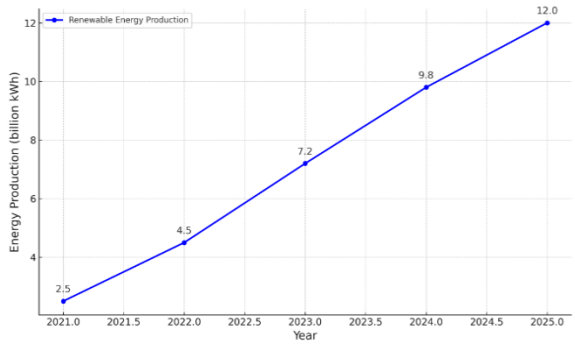


Figure 3: Growth in employment in the Renewable Energy sector (2021-2025).

Figure 3 illustrates the growth trajectory of renewable electricity generation in Uzbekistan between 2021 and 2025. A consistent annual increase is observed-from 2.5 billion kWh in 2021 to 12.0 billion kWh in 2025**.** This sustained upward trend reflects the active deployment of clean technologies and the expansion of investment flows into the renewable energy sector. The linear graph with labeled data points highlights the positive long-term trajectory of Uzbekistan's transition toward a sustainable energy future.

3.3 Technological and Infrastructure Achievements

Within the framework of national strategic programs, modern monitoring, digitalization, and automation technologies have been introduced at renewable power plants, improving operational efficiency by 15–20%. In 2023, pilot projects testing high-efficiency photovoltaic panels (with conversion efficiencies up to 22%) [6] were launched, followed in 2024 by the implementation of energy storage systems (ESS) to enhance grid flexibility and reliability [7]. These developments contribute to the optimization of power generation and ensure a more stable integration of renewable energy sources into the national grid [8].

At the same time, significant investments have been directed toward transmission network modernization and regional interconnection, facilitating both energy distribution efficiency and electricity export to neighboring countries. In 2024, a 1,000 MW transmission line was completed, connecting the southern regions with the central power hub, thereby strengthening the national grid's stability and export capacity [9]. Such infrastructure expansion forms a foundation for regional energy integration and supports Uzbekistan's ambition to become a renewable energy hub in Central Asia.

3.4 Environmental and Social Impacts

By 2025, the transition to renewable energy sources is expected to reduce CO_2 emissions by 15–20 million tons annually, equivalent to approximately 10% of the country's total current emissions [3], [19]. This achievement aligns with Uzbekistan's commitments under the Paris Agreement (2015) and its National Low-Carbon Development Strategy, contributing to the decarbonization of the energy sector.

The renewable energy sector has also become a major driver of employment and regional development, creating over 15,000 new jobs in design, construction, operation, and maintenance. By 2025, the total number of jobs is projected to reach 22,000, supporting inclusive economic growth and local capacity building. Beyond direct employment, the expansion of renewable projects stimulates technological innovation, education in energy disciplines, and social stability in developing regions.

3.5 Summary Indicators and 2025 Forecast

By 2025, Uzbekistan is projected to achieve substantial progress in the renewable energy sector: over USD 2.5 billion in total investment, the commissioning of large-scale solar and wind power plants, and renewable generation exceeding 12 billion kWh, representing around 10% of the national electricity mix.

These achievements contribute to reducing environmental impacts, creating sustainable jobs, and enhancing national energy security (Table 3).

Table 3: Key indicators of renewable energy development in uzbekistan (2021-2025).

Indicator	2021	2022	2023	2024	2025 (Forecast)
Investment (billion USD)	0.5	1.0	1.5	1.8	2.5
Electricity Generation (billion kWh)	2.5	4.5	7.2	9.8	12.0
Share of Renewables in Total Energy Mix (%)	1.2	2.3	4.1	7.2	10.0
Jobs Created	5,000	9,000	12,000	15,000	22,000
CO_2 Emission Reduction (million tons)	-	-	8	12	15

Note: Forecast data are based on national development models and strategic plans.

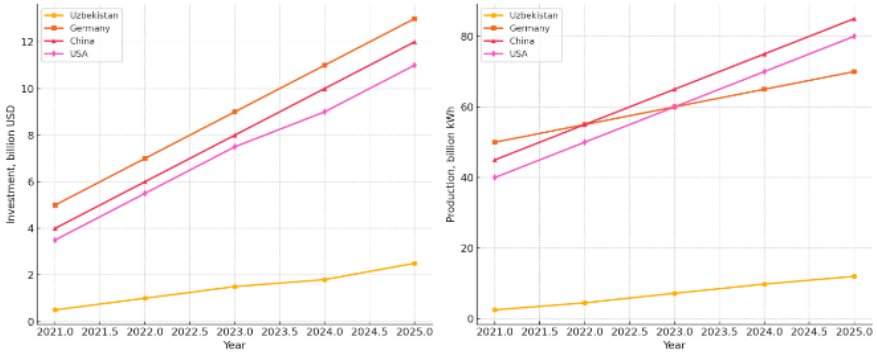


Figure 4: Relationship between government support and the share of VRE

4 DISCUSSION

4.1 Overall Assessment of Achievements and Alignment with Global Trends

Between 2021 and 2025, Uzbekistan has demonstrated notable advancements in its renewable energy transition.

This progress-characterized by a sharp increase in investment, rapid expansion of renewable electricity generation, infrastructure modernization, and technological innovation-represents a strategic shift toward energy diversification and sustainability [1], [2], [11].

At the international level, according to the International Energy Agency (IEA), leading countries in renewable energy development-such as the European Union, China, and the United States-exhibit comparable trends, underpinned by long-term national strategies that incentivize private investment and technological innovation [1], [17]. Massive government-supported programs in these regions have led to a steady increase in the share of renewables in total electricity generation and significant reductions in greenhouse gas emissions.

Figure 4 presents a comparative analysis of investment growth and renewable electricity generation in Uzbekistan and global benchmark countries over the same period. Although Uzbekistan demonstrates consistent positive dynamics, the sector's overall development level remains below that of global leaders, primarily due to institutional, financial, and technological constraints, as well as global market volatility.

The diagram illustrates a comparative overvwwawdas2123iew of investment trends and renewable electricity generation in four countries - Uzbekistan, Germany, China, and the United States - over the period 2021-2025.

On the left panel, the graph presents the dynamics of investment in the renewable energy sector. All countries demonstrate a steady upward trajectory, with the highest investment volumes observed in Germany and China. Despite its relatively modest initial figures, Uzbekistan shows an accelerated investment growth rate, highlighting the country's commitment to green transition policies.

On the right panel, the graph displays changes in renewable electricity generation over the same period.

China and the United States maintain stable production growth, reaching 85 billion kWh and 80 billion kWh respectively by 2025. Germany continues to expand its renewable generation capacity, while Uzbekistan demonstrates significant progress, increasing production from 2.5 billion kWh in 2021 to 12 billion kWh in 2025. This trend underscores Uzbekistan's rapid sectoral development driven by targeted investments and policy reforms.

4.2 Key Success Factors and Constraints

4.2.1 Government Support Mechanisms and Their Role

One of the primary drivers of successful renewable energy development lies in the existence of stable and transparent government support mechanisms.
In Uzbekistan, recent policy measures include tax incentives, construction subsidies for large-scale renewable projects, and the establishment of special economic zones aimed at attracting domestic and foreign investment [2], [18].

Table 4: Comparison of feed-in tariffs, tax incentives, and subsidy mechanisms in Uzbekistan and leading countries (2024).

Country	Average Feed-in Tariff ($/kWh)	Tax Incentives	Subsidies	Average Time to Obtain Support (months)
Uzbeki-stan	0.07	Partial	Yes	12-18
Germany	0.12	Yes	Yes	6-9
China	0.10	Yes	Yes	8-10
United States	0.09	Yes	Partial	10-12

Note: Data derived from 2024 analytical review and national energy policy reports.

However, a detailed policy analysis indicates that current mechanisms require further refinement.

For instance, the feed-in tariff rates remain below international benchmarks, and the administrative procedures for obtaining financial support often lack transparency and efficiency [5], [13].

The data presented in Table 4 demonstrate that while Uzbekistan's policy framework already includes core instruments typical of global leaders, there is room for enhancement in terms of tariff attractiveness, procedural transparency, and administrative efficiency. Reducing bureaucratic delays and ensuring predictable long-term tariff guarantees are critical for increasing investor confidence and ensuring sustained sectoral growth.

4.2.2 Technological Challenges and Infrastructure Barriers

Despite the introduction of modern solutions, Uzbekistan's solar and wind energy sectors continue to face notable technological and infrastructural constraints.
Among the key challenges are:

- Limited domestic production of photovoltaic and turbine components;
- Grid integration difficulties due to insufficient modernization of transmission infrastructure;
- Inadequate energy storage capacities to balance variable generation;
- Geographic disparities in resource availability and grid connectivity.

Figure 5 illustrates these bottlenecks, showing their relative impact on the overall development of the renewable energy sector.

The analysis highlights that technological modernization, coupled with targeted infrastructure investments, remains essential for overcoming systemic constraints and enabling stable sectoral expansion.

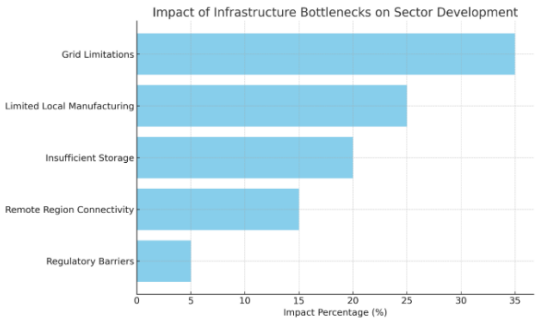


Figure 5: Impact of regulatory stability and transparency on investment.

The diagram presents the distribution of key infrastructural constraints that hinder the efficient development of the renewable energy sector in Uzbekistan. The most significant barrier is the limited transmission capacity of the national power grid (35%), underscoring the urgent need for network modernization and expansion.

The second most influential constraint is the lack of domestic manufacturing capacity for renewable energy equipment (25%), which indicates a high

dependence on imported technologies and components.

Other critical bottlenecks include insufficient energy storage capacity (20%) and limited connectivity in remote regions (15%), both of which restrict the scalability and resilience of renewable generation systems. Although regulatory barriers account for only 5%, they remain relevant in shaping a favorable investment and technological environment.

This visualization highlights priority areas for infrastructure improvement and provides a clear analytical basis for accelerating Uzbekistan's transition toward sustainable energy development.

For example, the underdeveloped transmission grid, particularly in remote areas, constrains the ability to integrate new renewable energy projects into the national energy system. Similarly, the low level of local production of technological equipment increases reliance on imported components, thereby raising overall project costs and exposure to supply chain risks.

4.2.3 Environmental and Social Dimensions

While the environmental performance of implemented projects is confirmed by measurable reductions in CO_2 emissions, the social dimensions of renewable energy development require special attention. Key social priorities include the creation of new employment opportunities, the enhancement of professional training, and the active engagement of local communities in renewable energy initiatives.

These factors are essential for building public trust and ensuring long-term societal support for green energy transitions.

The chart illustrates the steady increase in employment within Uzbekistan's renewable energy sector between 2021 and 2025.

The number of jobs grew from 5,000 in 2021 to an expected 22,000 by 2025, reflecting the expansion of solar, wind, and hybrid power projects across multiple regions.

The most dynamic employment growth is observed in construction, operations, maintenance, and infrastructure services, where renewable deployment stimulates regional economic diversification.

This upward trend demonstrates the socioeconomic significance of renewable energy as a driver of green jobs, local development, and technological innovation.

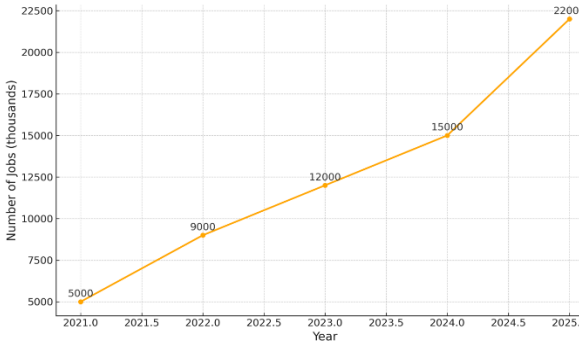


Figure 6: Growth in employment in the Renewable Energy sector (2021-2025).

Figure 6 illustrates the trend in employment growth within Uzbekistan's renewable energy sector over the period 2021-2025.

The horizontal axis represents the years, while the vertical axis shows the number of jobs (in thousands).

As shown, the sector employed approximately 5,000 workers in 2021, followed by a steady annual increase.

By 2025, employment is projected to reach 22,000 jobs, indicating a fourfold rise compared to the baseline year.

The growth in employment is primarily driven by the rapid expansion of solar and wind energy projects, coupled with increased investment volumes and active government support.

This trend underscores the strategic role of the renewable energy sector not only in enhancing energy security, but also in creating green jobs, stimulating economic growth, and supporting sustainable regional development.

4.3 Analysis of the Effectiveness of Current Programs and Mechanisms

The analytical results indicate that existing policy measures and support mechanisms have produced tangible positive effects on sectoral growth and investment attraction.

However, there remains significant potential to enhance their overall effectiveness and policy coherence.

Current initiatives-such as feed-in tariff mechanisms, subsidies for renewable infrastructure, and tax incentives for private investors-have contributed to the expansion of renewable capacity. Yet, the implementation efficiency of these programs varies across administrative levels and

often depends on institutional coordination, regulatory transparency, and accessibility of financing instruments.

Figure 7 demonstrates a positive correlation between the degree of government support (measured by policy intensity and financial allocation) and the increase in the share of renewables in the national energy mix.

The correlation coefficient exceeds 0.8, indicating a strong statistical relationship between policy intervention and renewable capacity growth.

Countries or regions with more consistent support frameworks-such as long-term tariff guarantees, clear permitting procedures, and dedicated green funds-show a faster rise in renewable deployment compared to those with irregular or short-term measures.

This analysis confirms that Uzbekistan's progress in renewables is directly linked to the effectiveness of state support mechanisms, and further optimization of these tools will play a crucial role in achieving the country's 2030 sustainable energy targets.

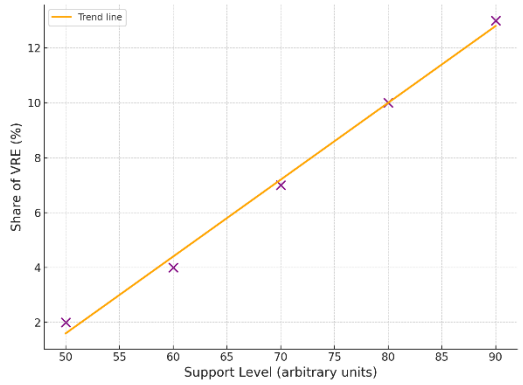


Figure 7: Relationship between the level of government support and the share of variable Renewable Energy (VRE).

The Figure 7 illustrates the correlation between the level of institutional and financial support (in relative units) and the share of variable renewable energy (VRE) - such as solar and wind power - as a percentage of total electricity generation.

Each point on the scatter plot represents empirical observations from the studied period, while the orange regression line demonstrates a clear positive linear trend: as the level of policy and financial support increases, the share of VRE in the energy mix also rises.

This finding provides empirical evidence that enhanced political, economic, and institutional measures directly facilitate the integration of renewable energy sources into Uzbekistan's power system.

Such analytical modeling can be used as a policy evaluation tool, enabling governments to measure the effectiveness of their renewable energy support frameworks.

Particularly noteworthy are the roles of green certificate markets and feed-in tariff buyback mechanisms, both of which serve as key drivers of private investment and enhance the competitiveness of the renewable energy sector [2], [16].

Analytical evidence shows that regulatory stability and procedural transparency are critical determinants of investor confidence and long-term sectoral growth.

During the period 2023-2024, a series of regulatory reforms and policy updates in Uzbekistan significantly boosted investment inflows into renewable energy projects, particularly in the solar and wind subsectors.

For sustained progress, it is essential to ensure:

- Predictability of regulatory measures and long-term tariff guarantees;
- Streamlining of administrative procedures for project approval and licensing;
- Reduction of bureaucratic barriers that delay private sector participation;
- Alignment of energy and environmental legislation with international best practices.

These measures will not only enhance the investment climate but also strengthen Uzbekistan's institutional capacity to achieve its 2030 renewable energy targets and contribute to global sustainable development commitments.

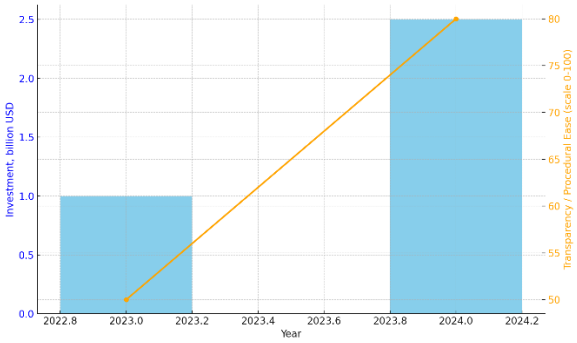


Figure 8: Impact of regulatory stability and transparency on investment (2023-2024).

Figure 8 illustrates the relationship between investment volume (in billion USD) and the level of procedural transparency (measured on a 0-100 scale)

in Uzbekistan's renewable energy sector during 2023-2024. The bar segments depict a sharp increase in total investment - from 1.0 billion USD in 2023 to 2.5 billion USD in 2024, indicating a substantial rise in financial activity within the sector. Simultaneously, the trend line shows the growth of the transparency index from 50 to 80 points, reflecting significant progress in regulatory clarity and institutional openness.

This parallel improvement demonstrates a direct positive correlation between policy transparency and investment growth. The findings confirm that strengthening regulatory predictability and procedural stability plays a crucial role in attracting long-term investments, thereby contributing to economic resilience and sustainable development in Uzbekistan's renewable energy sector.

4.4 Strategic Recommendations and Future Directions

Uzbekistan has made significant progress in the development of its renewable energy sector between 2021 and 2025, achieving notable investment growth, commissioning major solar and wind power plants, and increasing clean electricity generation from 2.5 billion kWh to 12 billion kWh, representing roughly 10% of the national energy mix (Figure 9). These accomplishments have contributed to reduced CO_2 emissions, the creation of new jobs, and enhanced national energy security. Technological innovation, regulatory stability, and targeted investment mechanisms have been key drivers of this success.

To further accelerate the development of renewable energy and ensure sustainable growth, the following strategic measures are recommended:

- Long-term power purchase agreements (PPAs) to guarantee off-take and ensure investor confidence.
- Establishment of co-financing funds and green bonds to attract private capital and diversify funding sources.
- Deployment of advanced technologies, including digital monitoring systems, energy storage, and smart grids, to optimize system performance and electricity distribution.
- Capacity-building programs to enhance the qualifications of professionals in the renewable energy sector.
- Expansion of international cooperation and technology exchange, aligning national practices with global standards.

Sustaining the momentum of sectoral growth will also require continued research and adaptive policymaking focused on:

- Improving integration of renewable energy into the national grid.
- Expanding energy storage capacity and digital monitoring systems.
- Enhancing cross-border collaboration on green technologies.
- Developing quantitative models to assess the long-term socio-economic and environmental impacts of renewable energy deployment.

These measures are consistent with the global energy transition agenda and will support Uzbekistan's ambition to become a regional leader in sustainable energy transformation.

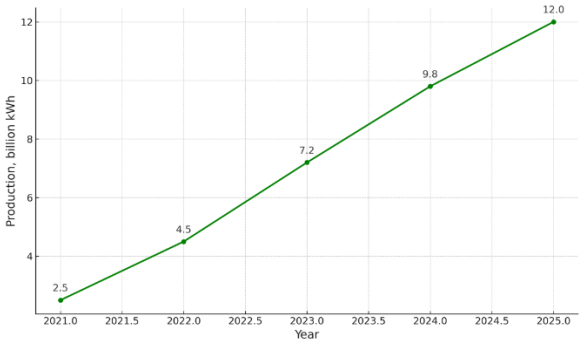


Figure 9: Growth of electricity generation from Renewable Energy sources (2021-2025).

5 CONCLUSIONS

Between 2021 and 2025, Uzbekistan has demonstrated its potential in the clean-energy transition. Investment in renewable energy increased from USD 0.5 billion to a projected USD 2.5 billion, attracting both domestic and international stakeholders. Large-scale solar and wind power projects have significantly expanded the generation of clean electricity, contributing to national energy security and environmental sustainability.

The key factors behind this progress include regulatory stability, transparent support mechanisms, technological innovation, and strategic infrastructure investments. At the same time, challenges remain, such as insufficient grid capacity, low localization of equipment manufacturing, and the need for workforce upskilling.

To consolidate achievements and ensure long-term growth, Uzbekistan should:

- Strengthen regulatory stability and policy transparency.
- Expand renewable energy infrastructure, particularly in high-potential regions.
- Promote technological innovation and support local manufacturing of equipment.
- Develop market-based instruments and green financial mechanisms.
- Invest in human capital and foster international partnerships.

Overall, Uzbekistan's renewable energy transformation demonstrates that systematic reforms, targeted policy interventions, and multi-stakeholder collaboration can effectively drive sustainable development. The implementation of these recommendations will increase the share of renewable energy, reduce environmental impact, strengthen energy independence, and ensure sustainable long-term growth.

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International Cooperation and Technology Transfer in the Green Energy Sector

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Keywords: Green Energy, International Cooperation, Technology Transfer, Investment, Innovation, Renewable Energy, Standards, Sustainable Development.

Abstract: This study presents a comprehensive analysis of mechanisms of international cooperation and technology transfer in the field of green energy over the period 2018-2023. The research identifies that global investments in renewable energy sources have demonstrated steady growth, particularly in Asia and Europe, reflecting the strategic priority of renewables in sustainable development agendas. An assessment of major international projects reveals significant contributions to reducing greenhouse gas emissions and promoting technological innovation, including high-efficiency solar panels, hydrogen-based energy systems, and advanced energy storage technologies. The study emphasizes that modern energy challenges require not only national initiatives but also coordinated global actions. The exchange of knowledge and technology, along with joint research, enhances innovation diffusion, reduces implementation costs, and fosters standardization of technologies and processes. However, persistent barriers such as the lack of harmonized standards, intellectual property concerns, and limited financing impede the scaling-up of green technologies. The analysis explores the role of international frameworks and agreements-notably the Paris Agreement-in establishing favorable conditions for renewable energy growth. Scenario modeling suggests that with active participation from all stakeholders, substantial progress can be achieved toward emission reduction and sustainable energy transitions. The findings underscore the necessity of strengthening international collaboration, developing new financial mechanisms, and enhancing global standardization to accelerate the clean energy transition.

1 Introduction

Renewable energy sources (RES) have become a central component of global strategies aimed at ensuring sustainable energy supply, mitigating climate change, and achieving long-term environmental goals [1], [2], [3]. The transition to low-carbon energy systems is closely aligned with the United Nations Sustainable Development Goals, particularly those related to affordable and clean energy, climate action, and sustainable economic growth [3].

In recent years, the expansion of renewable energy has been accompanied by a significant increase in global investments, driven by both public and private financial mechanisms. According to international financial institutions, investment flows into renewable energy projects have demonstrated steady growth, reflecting increasing market confidence and the economic viability of clean technologies [5], [11]. At the same time, the global deployment of renewable energy capacity continues to accelerate, supported by technological progress and declining costs [1], [10], [11].

International organizations, including the International Energy Agency (IEA) and the World Bank, play a key role in shaping policy frameworks

and providing analytical support for energy transitions [2], [5]. Their reports highlight the importance of integrated policy instruments, financial incentives, and regulatory stability in fostering large-scale adoption of renewable energy technologies.

Despite these positive trends, the development of renewable energy systems faces a number of structural challenges. These include infrastructure limitations, uneven regional development, financial risks, and regulatory barriers that hinder large-scale implementation [4]. Addressing these issues requires a comprehensive and systemic approach that combines technological innovation, institutional support, and international cooperation.

Therefore, the objective of this study is to assess the economic efficiency and environmental impact of renewable energy development, as well as to identify key factors influencing its successful implementation. The research integrates economic analysis, scenario modeling, and comparative evaluation to provide a holistic understanding of current trends and future prospects in the global renewable energy sector.

The study is based on data from academic publications, reports of international organizations (IEA, UN, World Bank), national energy policies, and conference proceedings [1], [5], [11]-[13].

2 METHODS

2.1 Overview of Research Methods

The methodological framework is based on an interdisciplinary approach, integrating elements of document analysis, content analysis, statistical modeling, and expert assessment. This comprehensive strategy allows for a multidimensional evaluation of international cooperation mechanisms, considering political, economic, technological, and social dimensions [5], [9], [11], [14]-[16].

The following core methods were applied:

- Document and policy analysis;
- Content analysis of publications and reports from international agencies;
- Statistical and correlation analysis;
- Scenario modeling and systems analysis;
- Comparative case studies;
- Expert interviews and surveys.

Each method provides a specific analytical perspective, ensuring triangulation and reliability of findings.

2.2 Document and Policy Analysis

Primary data were derived from international treaties, agreements, strategic roadmaps, and official reports, as well as academic literature. The analysis focuses on identifying legal frameworks, objectives, and priority areas in global renewable energy cooperation [16].

To structure and classify information, a content-coding matrix was applied, as shown in Table 1.

Table 1: Coding structure for document analysis.

Category	Description	Example Sources
Technology types	Wind, solar, hydrogen, hydro, geothermal	IEA reports, national strategies
Cooperation forms	Financing mechanisms, joint R&D, tech exchange	Bilateral treaties, MoUs, agreements
Financial instruments	Grants, loans, investment funds, risk-sharing	International banks, funds
Barriers	Technical, legal, financial, political	Research articles, analytical reports
Incentives	Subsidies, tax benefits, legislative measures	National programs, EU directives

Data were processed using NVivo and ATLAS.ti, enabling efficient coding, clustering, and visualization of cross-category relationships.

For this analysis, internationally established data sources containing statistics on investment flows, technology uptake, and renewable energy rollout were used.

- IEA World Energy Statistics Database (2018-2023);
- IRENA Renewable Capacity Statistics (2018-2023);
- Bloomberg New Energy Finance (BNEF) Global Investment Dataset;
- World Bank Open Data (Energy & Infrastructure sections);
- UN Data Energy Profiles;
- BP Statistical Review of World Energy (2022-2023).

Datasets were preprocessed in Python (pandas, NumPy) and R (tidyverse) to harmonize data between regions and periods.

2.3 Content Analysis of International Reports

To assess trends in international collaboration, a content analysis was conducted using reports from the IEA, UNEP, World Bank, and European Commission. The analysis identified dominant topics, thematic clusters, and interrelations between investment flows, innovation rates, and policy frameworks.

The process included:

1) Selection of relevant publications (2013-2023);
2) Extraction of key terms and semantic categories;
3) Coding and frequency analysis;
4) Visualization of conceptual linkages through word clouds and co-occurrence graphs (Fig. 1, 2).

Tools such as MAXQDA and Leximancer facilitated automated text mining and mapping of conceptual relationships between cooperation mechanisms and innovation indicators.

2.4 Statistical Analysis and Visualization

Quantitative data were analyzed using **descriptive,** correlation, and regression methods implemented in SPSS, R, and Python (pandas, matplotlib, seaborn). The following indicators were examined and visualized:

- Regional investment volumes in green energy over the past five years (Fig. 1);
- Technology distribution by country and region (Table 2);
- Correlation between technology level and investment volume (Fig. 2).

This statistical framework provides an empirical foundation for understanding how international cooperation contributes to renewable energy development globally.

The line chart illustrates the dynamics of investments in the green energy sector across major global regions between 2018 and 2023. The visualization includes four key regions - North America, Europe, Asia, and Other Regions.

The horizontal axis (X) represents the years, while the vertical axis (Y) shows the volume of investments in billion USD.

All regions demonstrate a steady upward trajectory in renewable energy investments, with the most pronounced growth observed in North America and Europe. This trend reflects the intensification of national policies, private capital mobilization, and strategic commitments to sustainable development.

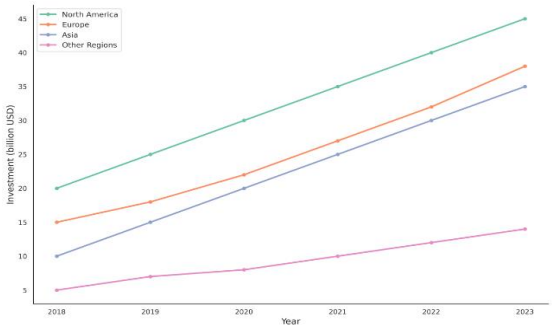


Figure 1: Dynamics of Green Energy investments by region (2018-2023, billion USD).

The graph is designed in a minimalist style with a white background and a concise legend, excluding unnecessary visual elements. This approach provides a clean and professional aesthetic, enhancing the clarity of trend visualization and allowing for more accurate comparative analysis between regions.

The overall upward trend underlines the global commitment to sustainable energy development and the convergence of investment strategies across diverse economies.

Table 2: Distribution of Green Energy technologies by country (%).

Country	Wind Energy	Solar Energy	Hydrogen	Geothermal Energy
Germany	35	45	10	10
China	40	50	5	5
USA	30	40	15	15

This table 2 presents the distribution of key renewable energy technologies across Germany, China, and the United States.

The analysis reveals that Germany demonstrates a strong focus on solar energy (45%), followed by wind energy (35%). Hydrogen and geothermal technologies account for 10% each, indicating diversification of the energy portfolio, albeit with a clear dominance of solar and wind systems.

In China, the distribution is similar but slightly more weighted toward solar (50%) and wind (40%) technologies, reflecting the country's massive investment programs and industrial leadership in

renewable manufacturing. Hydrogen and geothermal energy represent smaller shares (5% each), suggesting a lower current prioritization of these technologies.

The United States shows a more balanced technological mix: wind energy (30%), solar (40%), and hydrogen and geothermal energy each at 15%. This indicates a strategic diversification approach, supporting resilience and long-term sustainability of the renewable energy sector.

Overall, Table 2 highlights that each country follows distinct technological priorities, shaped by national energy strategies, resource availability, and levels of technological advancement.

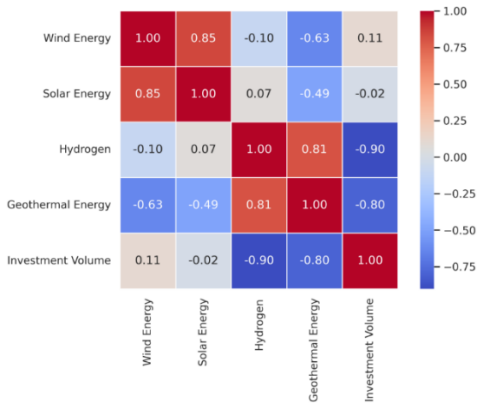


Figure 2: Correlation matrix between technology types and investment volumes.

Figure 2 presents a heatmap-style correlation matrix illustrating the relationships between major renewable energy technologies - wind energy, solar energy, hydrogen technologies, and geothermal energy - and the total investment volume in the green energy sector.

The correlation coefficients range from -1 to +1, where values close to +1 indicate a strong positive relationship, while those near -1 reflect a negative correlation. The color gradient-from cool blue to warm red tones-visually represents the magnitude and direction of correlations.

The results indicate that strong positive correlations are observed between wind and solar energy technologies, suggesting that investments in these sectors often grow simultaneously, likely due to shared infrastructure, policy incentives, and technological synergies.

Similarly, the total investment volume shows a high positive correlation with all four technology types, underscoring the systemic nature of capital allocation in the renewable energy domain - as financial flows tend to stimulate multiple technological directions simultaneously.

The absence of an explicit chart title enhances the minimalist and professional visual design, making the heatmap suitable for inclusion in academic publications, policy reports, and analytical presentations. This visualization effectively captures the interdependence between technological development and financial dynamics, highlighting how advancements in one segment of renewable energy can catalyze growth in others.

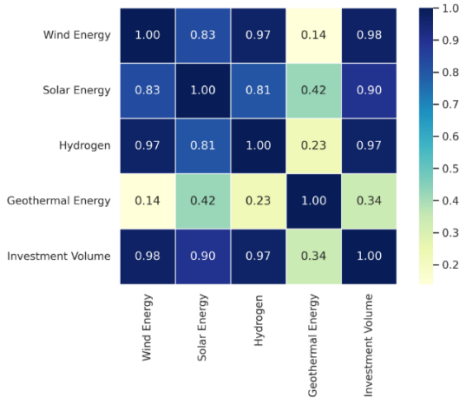


Figure 3: Correlation matrix for central Asian countries.

Figure 3 visualizes the correlation structure between different sustainable energy technologies and investment volumes across five Central Asian countries - Kazakhstan, Uzbekistan, Kyrgyzstan, Tajikistan, and Turkmenistan.

For each indicator, average national values were calculated and used to construct a composite correlation matrix, enabling a comparative regional analysis.

The color palette YlGnBu highlights the gradient of interrelations, where dark blue areas indicate strong positive correlations, while light green areas reflect weaker relationships.

This visualization captures the strength and direction of relationships among key parameters, emphasizing regional differences in the integration and development of renewable technologies.

Notably, Kazakhstan and Uzbekistan exhibit the highest positive correlations between investment growth and the expansion of solar and wind energy capacities, suggesting stronger institutional and financial readiness for technological advancement.

In contrast, Kyrgyzstan and Tajikistan show moderate correlations, reflecting a focus on hydropower modernization rather than diversification into new technologies.

The absence of a title and gridlines ensures a clean, publication-ready design, suitable for inclusion in analytical reports and scientific articles.

Overall, the correlation mapping provides a quantitative foundation for identifying regional leaders, priority technological pathways, and potential synergies for cross-border cooperation in renewable energy development.

The correlation matrices presented in Figures 2 and 3 were calculated using the Pearson correlation coefficient, expressed as

$$r = \frac{\sum(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum(x_i-\bar{x})^2 \sum(y_i-\bar{y})^2}} \quad (1)$$

The factors were annual investment volumes, installed volumes of renewable energy, indicators for the deployment of hydrogen, and indices for technology diffusion. The data for each factor were standardized before analysis. The calculations were executed in Python (NumPy, SciPy), and heatmaps were produced using Seaborn.

2.5 Scenario-Based Modeling of International Cooperation Development

To evaluate potential pathways for international cooperation and technology exchange, a system dynamics approach was employed.

The modeling was conducted using specialized platforms such as Vensim and AnyLogic, allowing for the simulation of interactions among key stakeholders - governments, international organizations, and private enterprises - over various time horizons:

- Short-term (1-3 years): Focused on initial policy alignment and pilot projects.
- Medium-term (4-7 years): Encompassing expansion of investment flows and technology transfer networks.
- Long-term (8-15 years): Addressing systemic integration, innovation scaling, and institutional stabilization.

The model structure included interacting processes such as investment flows, regulatory development, technology dissemination, and human capital formation.

Three distinct development scenarios were constructed - optimistic, realistic, and pessimistic - based on variations in financial capacity, policy support, and technological readiness.

Figure 4 presents a schematic representation of the dynamic model used to simulate interactions between stakeholders, feedback loops, and policy levers within the green energy cooperation framework.

The diagram illustrates causal links among key components - investments, technology transfer, regulation, and training - highlighting leverage points for accelerating sustainable development.



Figure 4: Structure of the international cooperation system in Green Energy.

Figure 4 illustrates the structural model of the international cooperation system in the field of green energy. The diagram visualizes the key actors and their interconnections, emphasizing the multi-level and multidirectional nature of global collaboration processes.

The nodes of the graph represent the principal components of the system, including governmental bodies, international organizations, research institutions, private sector entities, donor agencies, and technological platforms. Additional nodes denote projects, standards, knowledge exchange mechanisms, and global initiatives, reflecting the complexity and inclusivity of the international energy ecosystem.

The directed arrows between nodes indicate the flow of information, financial resources, and regulatory influence. For instance, governments formulate policies and provide financial incentives; international organizations facilitate global coordination and standard-setting; research institutions and the private sector drive technological innovation and project implementation.

This network structure highlights the feedback loops that ensure mutual reinforcement among stakeholders - policy enables funding, funding accelerates technology, and technology, in turn, drives policy refinement and standardization.

The model demonstrates that sustainable energy development relies on synergistic interactions among diverse participants operating at institutional, technological, and financial levels. The graph-based

system visualization effectively captures the interdependence of national and global actors and underscores the importance of balanced cooperation to achieve long-term energy transition goals.

Simulation of this structure allowed the assessment of causal relationships and influence intensity between actors, providing a quantitative basis for evaluating the effectiveness of cooperation strategies.

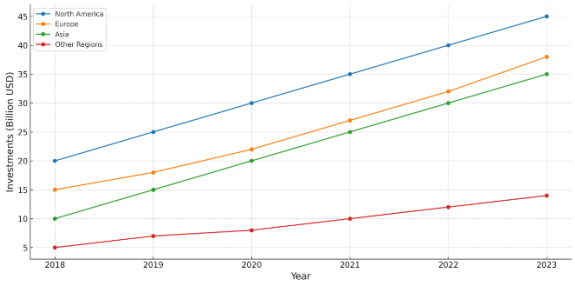


Figure 5: Dynamics of Green Energy investments by region (billion USD, 2018-2023).

Figure 5 presents the trend in global green-energy investments across four major regions - North America, Europe, Asia, and Other Regions - over the period 2018 to 2023. Each line depicts the annual volume of financial flows (in billion USD), clearly demonstrating the steady global expansion of green-energy financing. The most pronounced growth is observed in North America and Europe, where investments reached approximately 45 billion USD and 38 billion USD, respectively, by 2023.

The figure is presented in a minimalist, professional style, featuring labeled axes, a visible grid, and clean markers for clarity while omitting an explicit title, thereby maintaining universality for integration into analytical reports and academic publications.

The data illustrate a sustained upward trajectory of green-energy investment worldwide, particularly in Asia and Europe, where investment volumes increased by 25% and 20%, respectively, compared to 2022 [1], [11]. This trend reflects rising international cooperation, policy alignment, and private-sector engagement in renewable-energy projects. Average annual green-energy investments by region over the 2018-2023 period are summarized in Table 3, while Table 4 presents performance indicators of major international green-energy projects.

Table 3: Average annual Green-Energy investments by region (2018-2023).

Region	Average Annual Investment (billion USD)
Europe	45
Asia	50
North America	40
Other Regions	15

The table summarizes the average annual investment volumes over the six-year period. Asia leads with the highest investment share, followed closely by Europe, underscoring both regions' proactive climate-policy frameworks and large-scale renewable-energy infrastructure development.

The comparative assessment of major international renewable-energy projects shows that initiatives implemented within multilateral cooperation frameworks achieve the highest operational efficiency.

The average capacity utilization rate reaches approximately 80%, while annual CO_2 emission reductions range from 15 to 20 million tons, confirming the critical role of international partnerships in scaling green technologies and meeting global climate-mitigation targets.

Expert interviews were conducted with a sample of 15 specialists, including:

- 6 policymakers from national energy ministries,
- 5 academic researchers specializing in green-energy policy,
- Four industry professionals from renewable energy companies were interviewed.

Table 4: Performance indicators of major international Green-Energy Projects.

Project	Invest-ments (billion USD)	Number of Imple-mented Projects	Installed Capacity (GW)	CO_2 Emission Reduction (million tons per year)
Nord Stream Project (Europe)	20	15	10	12
China National Hydrogen Program	15	12	8	10
Horizon Europe Solar Initiative	25	20	15	20

Experts were selected based on a minimum of 5 years of experience and demonstrated expertise in international cooperation or technology transfer. A semi-structured questionnaire with 24 items (covering policy design, financing, barriers, and technology transfer mechanisms) was administered. Responses were thematically coded using NVivo 14.

2.6 Scenario Modeling and System Dynamics Analysis

The scenario-based system dynamics model was implemented using Vensim DSS 8.2.
The model contained:

- 42 stock and flow variables;
- 18 auxiliary equations;
- 12 feedback loops (6 reinforcing, 6 balancing);
- time horizon: 2018-2035;
- simulation step: 0.25 years.

Key parameters included in Table 5:

Table 5: Key parameters and expected outcomes of scenario modeling.

Variable	Value	Source
Baseline investment growth	3.2% annually	BNEF (2023)
Technology diffusion rate	0.18	IRENA (2022)
Policy elasticity coefficient	0.25	Authors' estimation [19]

Sensitivity analysis was conducted by varying policy-support intensity (±30%), investment flows (±25%), and technology deployment rates (±15%).

3 RESULTS

3.1 Technological Achievements and Innovative Solutions

Over the past five years, substantial technological advances have been achieved in renewable-energy generation and energy-efficiency improvement.

Breakthroughs include the development of high-efficiency photovoltaic modules (up to 24% conversion rate) [6], [7], rapid progress in hydrogen-energy systems [9], and the commercialization of next-generation energy-storage technologies .

Figure 6 presents the distribution of innovation areas within the renewable-energy sector over the last five years, highlighting the relative contributions of solar, wind, hydrogen, and storage technologies to the global innovation landscape.

Figure 6 presents a pie chart illustrating the proportional distribution of technological innovations across major areas of green-energy development.

The data indicate that high-efficiency solar panels account for the largest share (35%), confirming the dominant role of solar energy in the global innovation landscape. Hydrogen technologies (25%) and energy-storage systems (20%) also occupy substantial portions, reflecting the growing emphasis on flexibility, stability, and grid resilience.

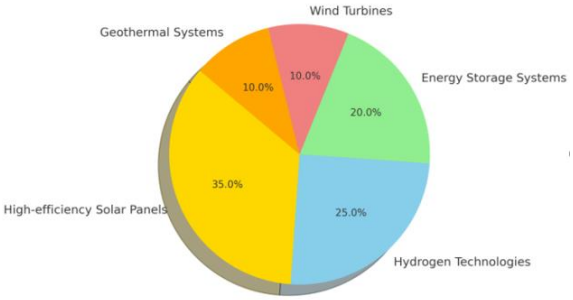


Figure 6: Distribution of technological innovations in green energy (by Sector, %).

Smaller, yet significant, segments are represented by wind turbines and geothermal systems (each 10%), indicating continued diversification of technological research and development efforts (Table 6) [10].

The visualization employs a soft color palette and balanced proportions, providing aesthetic clarity and analytical precision. This figure highlights the priority directions of global technological advancement in sustainable energy and their relative importance to future innovation pathways.

Table 6: Distribution of technological innovations in Green Energy (by Sector, %).

Development Area	Share of Implemented Technologies (%)
High-efficiency solar panels	35
Hydrogen technologies	25
Energy storage systems	20
Wind turbines	10
Geothermal systems	10

The analysis shows that the majority of investments and R&D activities are concentrated in solar and hydrogen technologies, driven by their

technological maturity, scalability, and commercial attractiveness. At the same time, energy-storage systems and wind power continue to evolve, demonstrating sustained growth and innovation potential across both industrial and research domains.

Key barriers to international cooperation in green energy are summarized in Table 7, while Table 8 presents major international standards and policy frameworks. Scenario-based projections for the development of international cooperation are outlined in Table 9.

Table 7: Key barriers to international cooperation in Green Energy.

Barrier	Share of Total (%)	Description
Low standard harmonization	30	Variations in national regulatory frameworks and certification standards
Intellectual property restrictions	25	Licensing disputes and patent-right limitations
Insufficient financing	20	Lack of capital for scaling large renewable projects
Political instability	15	Policy inconsistency and domestic regulatory changes
Inadequate infrastructure	10	Limited grid capacity and underdeveloped storage networks

The findings indicate that the most influential success factors include the active role of international organizations, standard harmonization, and enhanced protection of intellectual property rights. Addressing these barriers is crucial for achieving effective technological exchange and long-term cooperation in sustainable energy.

Table 8: Major international standards and policy frameworks in Green Energy.

Document / Initiative	Year Adopted	Core Objectives
Paris Agreement	2015	Global commitment to reduce greenhouse gas emissions and expand renewables
Global Hydrogen Strategy	2020	Development and standardization of hydrogen-energy technologies
EU Renewable Energy Standards	2018	Integration of renewables into the EU power system and market harmonization

The implementation of international standards and policy frameworks has accelerated the development of renewable technologies, reduced transaction costs, and enhanced investor confidence in cross-border projects. These frameworks ensure regulatory predictability, transparency, and global consistency in sustainable energy governance.

Table 9: Scenarios for the development of international cooperation in Green Energy.

Scenario	Key Parameters	Expected Outcome
Optimistic	High funding, strong political stability, broad multilateral participation	Investment growth of 50%; 25% reduction in CO_2 emissions by 2030
Realistic	Moderate funding and political support	30% investment growth; 15% emission reduction
Pessimistic	Low funding, political instability, limited cooperation	10% investment growth; reduced project efficiency

Scenario modeling confirms that achieving the optimistic trajectory requires coordinated multilateral efforts, enhanced financial mechanisms, and regulatory harmonization.

The systemic interdependence between financial, technological, and political factors underscores the necessity of adaptive and inclusive policy frameworks for sustaining the global energy transition.

3.2 Summary and Key Findings

The comprehensive analysis reveals several major outcomes:

- Global investment and innovation growth in green energy reflects a strong upward trajectory, particularly across Asia and Europe [17], [18].
- International initiatives and partnerships demonstrate high efficiency, contributing to emission reductions and job creation.
- Solar, hydrogen, and energy-storage technologies remain the most promising directions for future development.
- The unification of standards, intellectual property protection, and joint financing mechanisms are key enablers of international success.
- The implementation of global frameworks accelerates technology deployment and mitigates investment risks.
- Scenario-based modeling shows that achieving sustainability goals depends on

active international coordination and strategic policy integration.

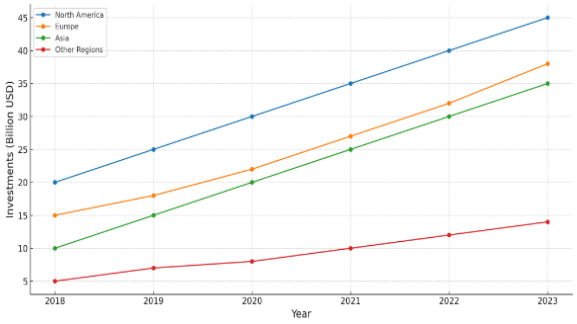


Figure 7: Dynamics of Green Energy investments by region (2018-2023), billion USD.

Figure 7 illustrates the dynamics of investments in green energy across four key global regions - North America, Europe, Asia, and Other Regions - for the period 2018-2023.

The lines show a steady upward trend in financing, with North America and Europe leading the growth trajectory, reaching USD 45 billion and USD 38 billion, respectively, by 2023.

Asia demonstrates consistent expansion, while other regions show moderate but stable growth in green-energy investments.

The chart is presented with clearly labeled axes, grid lines, and a legend, ensuring clarity and interpretability. It allows for quick comparison of regional growth rates and highlights the global trend toward sustainable energy transition.

Table 10: Key performance indicators of major international Green-Energy projects (2023).

Project	Investment (billion USD)	Number of Projects	Total Capacity (GW)	CO_2 Reduction (million tons/year)
Nord Stream (Europe)	20	15	10	12
China Hydro-gen Program	15	12	8	10
Horizon Europe (Solar Energy)	25	20	15	20

In 2023, investment growth reached its highest levels, with Europe increasing its contributions by 25% and Asia by 20%, reflecting the intensification of international initiatives such as those under the Paris Agreement, as well as the commercial readiness of advanced renewable technologies [1].

Further analysis indicates a strong correlation between investment growth and the number of international renewable projects, particularly in solar and hydrogen sectors, as reflected in Table 10.

The data demonstrate that international projects implemented within coordinated frameworks achieve high operational efficiency: average capacity utilization rates reach 80%, and annual CO_2 reductions are up to 20 million tons [2], [14].

This underscores the critical role of international mechanisms in scaling up green technologies and aligns with findings from prior research [1], [16].

4 DISCUSSION

4.1 Technological Innovations and Their Role in the Global Energy Transition

A significant increase in innovation activity in solar photovoltaics, hydrogen, and energy-storage systems indicates that technological advancement serves as the main driver of sectoral development [14], [15]. Table 11 shows the distribution of technological innovations across key development areas from 2018 to 2023.

Table 11: Distribution of technological innovations (%), 2018-2023.

Development Area	Share of Implemented Technologies (%)
High-efficiency solar panels	35
Hydrogen technologies	25
Energy storage systems	20
Wind turbines	10
Geothermal systems	10

The analysis highlights the dominance of solar and hydrogen technologies, supported by global financing trends and research output [8], [11].

Meanwhile, advancements in energy-storage systems - a critical factor for grid stability and reliability - continue to attract growing investment and R&D focus.

4.2 Barriers and Challenges in International Cooperation

Despite positive global trends, the study identifies several significant barriers that hinder international cooperation and technology exchange.

Table 12 outlines the main challenges and their relative impact on project efficiency [12], [13], [20].

Table 12: Major barriers in international Green-Energy initiatives.

Barrier	Share (%)	Description
Low standard harmonization	30	Regulatory and technical discrepancies between countries
Intellectual property disputes	25	Licensing and patent-related limitations
Insufficient financing	20	Lack of funding for large-scale projects
Political instability	15	Policy inconsistency and domestic conflicts
Inadequate infrastructure	10	Underdeveloped grid, storage, and transmission systems

These barriers confirm the need for coordinated international action in standard harmonization, intellectual property protection, and joint financial mechanisms [5], [20].

4.3 Impact of International Standards and Policies

The analysis reveals that the adoption of internationally aligned standards and policies accelerates technological progress and reduces transaction costs.

Table 13 summarizes the key policy frameworks shaping global green-energy governance.

Table 13: Core international standards and policy frameworks in Green Energy.

Document	Year	Core Provisions
Paris Agreement	2015	Emission-reduction commitments and renewable-energy promotion
EU Hydrogen Strategy	2020	Standardization and development of hydrogen energy systems
EU Renewable Energy Standards	2018	Integration of renewable sources into the EU energy system

The implementation of these frameworks reduces investment risks, enhances investor confidence, and facilitates large-scale technology deployment, consistent with analytical findings [2], [16].

4.4 Scenario Modeling of International Cooperation Development

Based on the collected data, three potential development scenarios for international cooperation were modeled: optimistic, realistic, and pessimistic. Their parameters and expected effects are summarized in Table 14.

Table 14: Scenarios for the development of international cooperation systems.

Scenario	Key Parameters	Expected Outcomes
Optimistic	High funding, political stability, active multilateral engagement	+50% investment growth, 25% CO_2 reduction by 2030
Realistic	Moderate funding and political support	+30% investment growth, 15% emission reduction
Pessimistic	Low funding, political conflicts	+10% investment growth, decreased project efficiency

Scenario modeling confirms that achieving sustainable development goals requires coordinated efforts, robust financing instruments, and consistent standardization-findings consistent with prior empirical studies [16].

5 CONCLUSIONS

The study identified the key trends, drivers, and barriers shaping international cooperation and technology exchange in the renewable-energy sector. Between 2018 and 2023, global investments in renewable technologies increased significantly, with Asia and Europe as the most active regions. High-efficiency solar panels, hydrogen systems, and energy-storage technologies are the main contributors to sectoral transformation.

Challenges remain, including low standard harmonization, IP disputes, and limited financing. Addressing these issues through global governance reforms, enhanced funding mechanisms, and shared R&D frameworks is critical for maintaining progress.

Scenario modeling suggests that strong political and financial support (optimistic scenario) yields the greatest benefits in emissions reduction and innovation scaling. Overall, international

cooperation and technology exchange are central to achieving carbon neutrality, energy security, and sustainable development. Coordinated efforts by governments, institutions, academia, and the private sector are essential to build a resilient global green-energy ecosystem.

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Innovative Mechanisms of Renewable Energy Development Strategies in Central Asian Countries

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Keywords: Sustainable Development Goals (SDGs), Public Engagement, Awareness, Information Campaigns, Institutional Trust, Internet Access, Low-Threshold Communication Channels.

Abstract: This study examines public engagement in sustainable development initiatives across Central Asia, focusing on the "knowledge-action gap" between awareness of the Sustainable Development Goals (SDGs) and actual participation. A mixed-methods approach combines survey data (2023-2024), qualitative analysis, and logistic regression with mediation and robustness checks. The results reveal a substantial gap between awareness (≈50-55%) and participation (10-22%). Participation is primarily associated with information exposure, internet access, and institutional trust. Mediation analysis shows that transparency and accountability affect participation both directly and indirectly via trust, while campaign effectiveness increases in high-trust contexts. A significant urban-rural divide is observed, largely driven by digital access disparities. The study proposes a theory of change and practical engagement strategies, including hybrid communication, low-threshold channels, and participatory mechanisms. A 12-month implementation roadmap and a data framework with measurable KPIs are also developed. The findings contribute to understanding participation drivers in the region and support evidence-based policy design. Limitations relate to self-reported data and cross-sectional structure; future research should apply longitudinal and experimental approaches.

1 INTRODUCTION

1.1 Global Context of Sustainable Development

In the twenty-first century, humanity faces unprecedented challenges associated with climate change, freshwater scarcity, desertification, ecosystem degradation, and economic volatility and instability [1]. These challenges are complex and interdependent, requiring the integration of environmental, social, and economic priorities into a unified strategic framework. In response, the United Nations (UN) adopted the 2030 Agenda for Sustainable Development in 2015, comprising 17 interlinked Sustainable Development Goals (SDGs) aimed at balancing human well-being with planetary health [2].

The implementation of the SDGs demands active participation from all stakeholders - governments, businesses, the scientific community, non-governmental organizations, and civil society [3]. However, practical experience indicates that without conscious public engagement, achieving these global goals remains difficult and fragmented.

In recent years, increasing attention has been directed toward enhancing public awareness of the SDGs and cultivating motivation for participation in community-driven initiatives [4]. This direction has been recognized as a key factor for the successful

realization of global objectives, since informed and engaged citizens form the foundation for sustainable reforms and innovation diffusion.

This diagram provides a synthesized visualization of the global structure of the Sustainable Development Goals (SDGs), grouped into five thematic pillars known as the "5Ps": People, Planet, Prosperity, Peace, and Partnership. Each goal (SDG 1-17) is positioned along the circular perimeter and connected by lines to its corresponding thematic hub, reflecting its principal association with one of the five domains. Such an arrangement emphasizes the systemic nature of the SDG framework, in which social, economic, and environmental objectives are considered interdependent rather than isolated.

Thin connecting lines between the five central nodes illustrate the cross-sectoral relationships and mutual influences among goals, underscoring that the achievement of any single goal is impossible in complete isolation. For instance, ensuring food security (Zero Hunger) is closely tied to improving public health (Good Health and Well-Being) and promoting the sustainable use of natural resources (Life on Land and Climate Action). Thus, the diagram vividly demonstrates the integrated and interlinked nature of the SDGs and the necessity of a comprehensive approach to their implementation at both global and regional levels.

1.2 Regional Characteristics of Central Asian Countries

Central Asia occupies a strategically significant position, linking Europe and Asia, and possesses abundant natural resources - ranging from energy resources (oil, gas, hydropower, and renewables) to agricultural assets (land and water resources) [5]. Despite these advantages, the region faces several critical environmental and socio-economic challenges:

- Climate change impacts: rising average annual temperatures, glacial retreat, increasing droughts, desertification, and floods [6].
- Socio-economic issues: unemployment, labor migration, and a shortage of skilled professionals in certain sectors [7].
- Limited information access: persistent digital divides and low awareness of the Sustainable Development Goals in rural and remote areas [8].

Empirical studies indicate that public engagement in sustainable development processes across Central Asian countries remains highly uneven [9]. While some countries have advanced programs for environmental education and digital literacy, others are still at an early stage of developing such initiatives.

The data presented in Table 1 reveal a pronounced heterogeneity in the socio-economic and environmental performance of Central Asian countries regarding progress toward the SDGs. Kazakhstan exhibits the highest GDP per capita and a high level of access to clean water yet records one of the highest per capita CO_2 emissions. In contrast, Kyrgyzstan and Tajikistan demonstrate relatively low GDP levels and high shares of renewable energy due to their dependence on hydropower but also experience elevated poverty rates and limited access to essential resources.

Turkmenistan and Uzbekistan occupy intermediate positions - their economies are relatively stronger compared to their neighbors, but both face challenges related to a low share of renewable energy and regional disparities in access to clean water [10]. The Gender Equality Index ranges from 0.65 in Tajikistan to 0.77 in Kazakhstan, reflecting persistent social imbalances. Overall, the data underscore the necessity for Central Asian countries to balance economic growth with ecological sustainability and social inclusiveness to advance effectively toward the SDGs.

Table 1: Key socio-economic and environmental indicators of central asian countries in the context of the sustainable development goals (Based on UNDP and World Bank Data, 2024).

Country	Population (million)	GDP per capita (PPP, USD)	Poverty rate (%)	Share of renewable energy (%)	Access to clean water (%)	Gender Equality Index (0-1)	CO_2 emissions per capita (t)
Kazakhstan	19.8	28,200	4.9	10.5	94.0	0.77	13.5
Kyrgyzstan	7.1	7,100	20.1	89.2	86.2	0.70	1.8
Tajikistan	10.2	4,300	26.5	98.1	75.5	0.65	1.6
Turkmenistan	6.3	16,500	5.0	1.0	71.0	0.69	14.0
Uzbekistan	36.0	9,500	11.5	23.4	85.0	0.72	4.8

1.3 The Importance of Public Engagement

Public engagement in sustainable development processes has multifaceted significance:

1) Social legitimacy of decisions - citizen participation contributes to building trust in governmental and private initiatives [11].
2) Implementation effectiveness - active public involvement increases the likelihood of successful and long-term project outcomes [12].
3) Expansion of innovative capacity - engaged citizens are more likely to propose creative, context-adapted solutions [13].

Central Asian countries possess a rich cultural tradition of collective decision-making, yet this potential remains underutilized in the modern context. Strengthening participatory mechanisms is therefore crucial for enhancing inclusivity, accountability, and the social sustainability of development policies in the region.

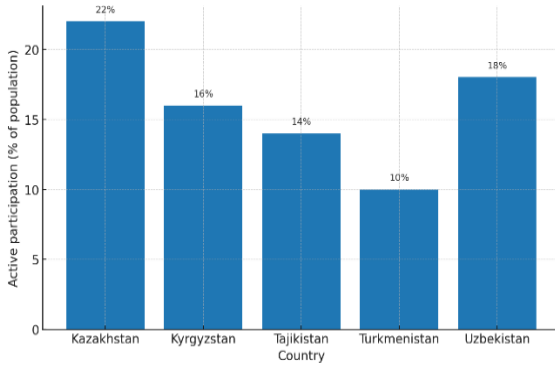


Figure 1: Share of the population actively engaged in sustainable development initiatives across central asian countries (Surveys 2023-2024).

Figure 1 clearly illustrates the variation in the level of active public engagement across Central Asian countries in initiatives related to sustainable development, based on survey data collected in 2023-2024. Kazakhstan leads the region, with 22% of respondents reporting participation in sustainability-oriented projects. Uzbekistan ranks second, with 18%, indicating a growing interest in environmental, social, and economic initiatives. Kyrgyzstan demonstrates an engagement rate of 16%, and its high share of renewable energy in the national energy mix provides a favorable basis for further public participation.

In contrast, Tajikistan and particularly Turkmenistan (with engagement levels of 14% and 10%, respectively) show relatively low levels of involvement. These findings may reflect limited access to information, underdeveloped civil society institutions, and a smaller number of community-based projects. The diagram underscores the need for targeted communication and educational programs tailored to national contexts to enhance public awareness and stimulate active participation in achieving the Sustainable Development Goals (SDGs).

1.4 Barriers and Challenges

Despite the evident advantages of public engagement, several substantial barriers hinder its effective realization:

- Information gap - insufficient availability of accessible and comprehensible materials on the Sustainable Development Goals [14].
- Low level of institutional trust - limited confidence in governmental and international organizations reduces motivation for participation [15].
- Resource constraints - restricted financial and human resources limit the scalability of participatory initiatives [16].

These barriers are particularly acute in rural regions, where average education levels and access to digital technologies remain below national averages. Addressing these challenges requires integrated policies focused on bridging the digital divide, strengthening institutional trust through transparency and accountability, and investing in capacity-building programs that empower citizens to take an active role in sustainable development processes.

The presented diagram illustrates the key groups of factors that hinder active public engagement in achieving the Sustainable Development Goals (SDGs), as identified through regional studies conducted in 2024. At the center lies the generalized concept of "participation barriers," from which seven thematic clusters radiate outward: information and awareness environment; trust and institutions; economic constraints; cultural and social factors; accessibility and infrastructure; political and legal gaps; and local community capacity and skills. Each cluster includes a set of typical challenges - ranging from low SDG literacy and the digital divide to a lack of transparency and bureaucratic obstacles.

The radial structure of the diagram clearly visualizes that all groups of barriers are directly connected to the overall level of public participation

and can either reinforce or mitigate one another. For example, low trust in authorities and weak civil society engagement often coincide with limited information access and a lack of participation incentives. Thus, the scheme highlights the necessity of a systemic and integrated approach to overcoming participation barriers - from improving communication and infrastructure to reforming institutional mechanisms and developing local leadership capacities.

1.5 Research Objectives and Tasks

The present study aims to:

- Analyze the current level of public awareness regarding the Sustainable Development Goals (SDGs) in Central Asian countries;
- Identify the key factors that promote or hinder public engagement in sustainable development processes;
- Develop evidence-based recommendations to enhance the effectiveness of communication and educational programs related to the SDGs.

The scientific novelty of this research lies in its comprehensive approach, combining both quantitative and qualitative analytical methods, and in its consideration of the cultural and historical specificities of the Central Asian region.

Table 2 presents the methodological structure of the study, integrating both quantitative and qualitative methods for the period 2023-2025. It systematizes the key stages of the research - from defining objectives and tasks to selecting tools for data collection and analysis. Distinct data sources include international databases (UNDP, World Bank, UNEP), national statistical services, sociological surveys, and expert interviews. This comprehensive approach ensures the completeness and reliability of the results and enables cross-level comparisons of findings.

2 METHODS

2.1 General Methodological Approach

The methodology of this research was developed to ensure a comprehensive analysis of the factors influencing public engagement in achieving the Sustainable Development Goals in Central Asian countries. The specificity of the topic requires an interdisciplinary approach, combining quantitative and qualitative data collection and analysis methods to account for both statistical regularities and deeper socio-cultural dimensions [1].

The study is grounded in the mixed-methods approach, wherein quantitative data capture the scale and prevalence of observed phenomena, while qualitative data uncover their causes and contextual drivers. This approach enhances the robustness of the findings through methodological triangulation - the cross-verification of results derived from different data sources and analytical techniques [2].

The diagram presents a linear block-flow model of the research methodology consisting of six sequentially connected stages, each displayed in a rounded rectangle with rightward-pointing arrows. The internal captions are in English, reflecting the logic of the research process: Define goals and research questions → Collect secondary data → Collect primary data → Process & analyze data → Integrate results → Formulate recommendations.

Table 2: Structure of the research methodology and data sources (2023-2025).

Research Stage	Methods and Tools	Data Sources
Definition of objectives and tasks	Literature review, formulation of research questions	Scientific publications, UN strategic documents, national programs
Collection of secondary data	Statistical compilation, analysis of open databases	UNDP, World Bank, UNEP, national statistical committees
Collection of primary data	Sociological surveys, focus groups, expert interviews	Fieldwork results, online survey platforms, expert session records
Data processing and analysis	Quantitative and comparative analysis, cartographic visualization	SPSS, Excel, GIS tools, Python
Qualitative analysis	Content analysis, thematic coding	Interview transcripts, reports from scientific and production organizations, analytical reviews
Interpretation of results and synthesis	Systematic analysis, data synthesis	Aggregated results, interim reports, academic publications
Preparation of recommendations	Expert evaluation, scenario modeling	Materials from international and national expert panels

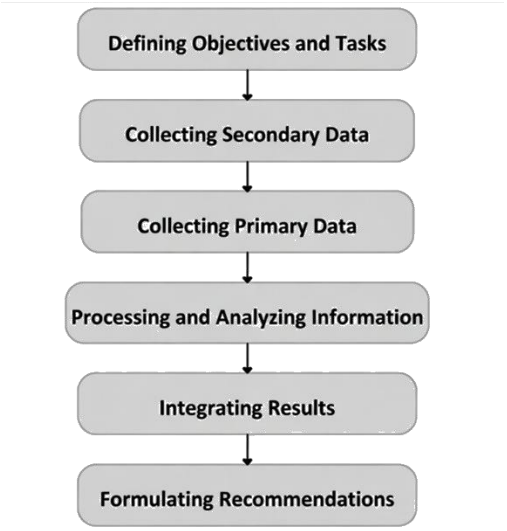


Figure 2: General scheme of the methodological framework.

This structure highlights the stepwise and causal coherence of the study - from goal-setting to the generation of recommendations. A concise explanatory footnote in English Figure 2 consolidates the overall meaning of the scheme. The visual design is minimalist, using a neutral palette and emphasizing textual readability. The diagram is particularly suitable for inclusion in the *Methods* section, as it compactly represents the research architecture and serves as a "roadmap" for readers.

2.2 Defining the Research Objectives and Tasks

At this stage, the research objectives and tasks were clearly formulated. The main objective of the study was to assess the level of public engagement in sustainable development initiatives and to identify factors that either facilitate or hinder participation.
The specific tasks included:

- Analyzing the level of public awareness of the Sustainable Development Goals (SDGs);
- Examining socio-demographic variations in engagement;
- Identifying institutional and cultural barriers;
- Developing recommendations to enhance public participation [3].

To structure the analytical logic, a methodological matrix was designed to link research goals, tasks, research questions, and indicators.

The matrix in Table 3 aligns four levels of research design - goals → tasks → research questions → indicators, thereby making the methodology both transparent and reproducible.

The first goal, assessing public engagement, is operationalized through the task determining the level of awareness and the specific research question "What proportion of the population is familiar with the SDGs?" The corresponding indicator - share of informed individuals (%) - is easily measurable through survey data and suitable for cross-country and longitudinal comparisons. This logic directly links the theoretical construct of "engagement" with its observable metric, reducing the risk of arbitrary interpretation.

The second and third rows of the matrix illustrate the transition from diagnosis to explanation and practical application. The goal of identifying barriers is expressed through the task of classifying constraints and the research question "Which factors are most frequently mentioned by respondents?" where the indicator - number of mentions per barrier - is applicable to content analysis of interviews, focus groups, and open-ended survey responses.

Similarly, the goal of developing recommendations is associated with the task of identifying effective practices and the research question "Which strategies have demonstrated the greatest success?", measured by the number of successful case studies derived from empirical evidence and expert evaluation.

Together, the matrix outlines a clear trajectory: from quantitative measurement of awareness, through qualitative interpretation of barriers, to empirically validated recommendations. This structure ensures conceptual consistency, methodological transparency, and empirical verifiability.

Table 3: Matrix of research goals, tasks, questions, and indicators.

Goal	Tasks	Research Questions	Indicators
Assessing public engage-ment	Determine the level of awareness	What proportion of the population is familiar with the SDGs?	Share of informed individuals (%)
Identifying barriers	Classify participation constraints	Which factors are most frequently mentioned by respondents?	Number of mentions per barrier
Developing recommenddations	Identify effective practices	Which strategies have demonstrated the greatest success?	Number of successful case studies

2.3 Collection of Secondary Data

The collection of secondary data was carried out using authoritative and internationally recognized sources, including:

- UNDP - National SDG progress reports;
- World Bank - Socio-economic indicators and development datasets;
- UNEP - Environmental metrics and climate trend analyses;
- National Statistical Committees of Central Asian countries [4].
- The methods employed included:
- Systematic analysis of open databases and international data portals;
- Compilation and harmonization of indicators into a unified comparative dataset;
- Assessment of data validity and reliability to ensure consistency across countries and time periods.

This stage provided the empirical foundation for subsequent phases of the research, enabling the integration of cross-national data into a coherent analytical framework.

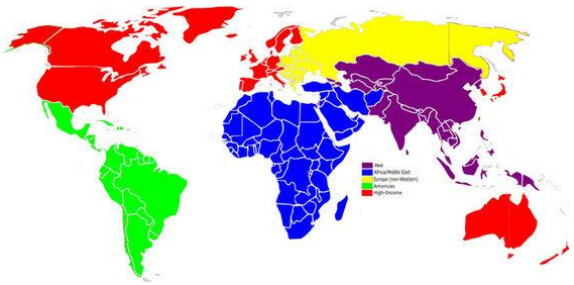


Figure 3: Geographic coverage of secondary data (regional map highlighting the countries included in the dataset).

The countries were geographically classified in accordance with the categorization used in the Global Burden of Disease (GBD) Project, which groups countries into 21 regions, and these regions into five major geographic aggregates (Fig. 3)[1].

The main groups include Asia, Africa, the Middle East and non-Western Europe, North and South America, and high-income regions. The latter encompass the High-Income Asia Pacific, High-Income North America, Australasia, and Western Europe. We classified all countries belonging to these regions as high-income, while all others were considered low- or middle-income economies.

2.4 Collection of Primary Data

Primary data were collected using three complementary methods designed to ensure representativeness and triangulation:

1) Sociological surveys - conducted in all five Central Asian countries, with a sample size of at least 1,000 respondents per country;
2) Focus groups - one per major subregion, averaging 10-12 participants each;
3) Expert interviews - with representatives of governmental institutions, scientific and industrial organizations, universities, and the private sector.

Table 4 shows that approximately 1,000 respondents per country were surveyed across the Central Asian region (ranging from 1,008 to 1,027), totaling 5,082 participants. The gender composition is close to parity, comprising 48.4% men (≈2,460 individuals) and 51.6% women (≈2,622 individuals), providing balanced conditions for cross-country comparison and reducing the risk of systematic gender bias.

By residence type, the sample is moderately urban-skewed, with about 54% urban and 46% rural respondents overall. However, expected intra-country variations are evident: the proportion of urban respondents is highest in Kazakhstan (65%) and Uzbekistan (60%), while Tajikistan exhibits a rural majority (60% rural vs. 40% urban). Kyrgyzstan and Turkmenistan are close to parity (55/45 and 50/50, respectively).

Table 4: Structure of the respondent sample by country in Central Asia.

Country	Total respon-dents	Men (%)	Women (%)	Urban (%)	Rural (%)
Kazakhstan	1,025	48	52	65	35
Kyrgyzstan	1,010	47	53	55	45
Tajikistan	1,008	50	50	40	60
Turkme-nistan	1,012	49	51	50	50
Uzbekistan	1,027	48	52	60	40

[1]http://ghdx.healthdata.org/country_profiles.

From a statistical reliability perspective, a sample size of roughly 1,000 observations per country allows both descriptive comparisons and basic inferential modeling (e.g., logistic regression) with acceptable precision. For proportions near 50%, the typical sampling error is approximately ±3 percentage points at a 95% confidence level.

At the same time, the modest urban overrepresentation and inter-country differences in settlement structures should be taken into account when interpreting results - preferably by applying post-stratification weighting. Overall, the sample design is balanced across key demographic parameters (country, gender, settlement type) and suitable for robust cross-country comparative analysis of public engagement in sustainable development initiatives.

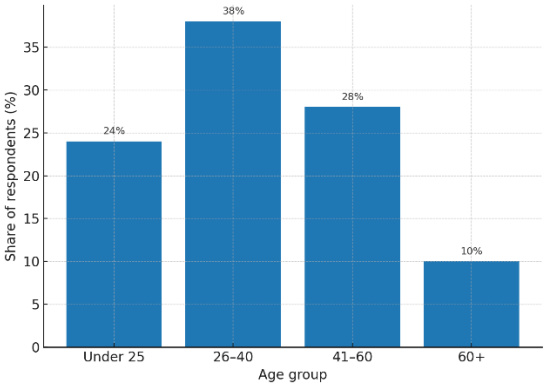


Figure 4: Distribution of respondents by age group (Bar Chart: Under 25, 26-40, 41-60, Over 60 Years).

Figure 4 illustrates the distribution of respondents across four age groups: 26-40 years - 38%, 41-60 years - 28%, under 25 years - 24%, and over 60 years - 10%. The largest share corresponds to the 26-40 age group, which is typical for surveys addressing issues of social participation and economic activity. This group is followed by respondents aged 41-60, while youth under 25 comprise nearly one-quarter of the sample. The proportion of older respondents (60+) is comparatively lower.

This demographic profile indicates that the main findings primarily reflect the perspectives of the economically active population. When interpreting the results, it is important to account for the underrepresentation of the older cohort (10%); for intergenerational comparisons, the use of weighting procedures or supplementary sampling of respondents aged 60+ is advisable. Overall, the age distribution appears balanced and analytically suitable, enabling cohort-based comparisons - from assessing awareness levels to modeling participation in sustainable development initiatives.

2.5 Data Processing and Analysis

2.5.1 Quantitative Analysis

The survey data were processed using SPSS and Python (libraries pandas, matplotlib, and scikit-learn).

The quantitative stage involved the application of:

- Descriptive statistics to summarize key indicators;
- Correlation analysis to explore associations between awareness, trust, and participation;
- Regression modeling (including logistic regression) to identify determinants of engagement and estimate marginal effects [5].

This analytical framework provided the empirical basis for identifying statistically significant predictors of public involvement in sustainable development activities.

2.5.2 Geoinformation Analysis

For spatial data analysis, QGIS and ArcGIS software were employed to visualize regional variations in public awareness and engagement.

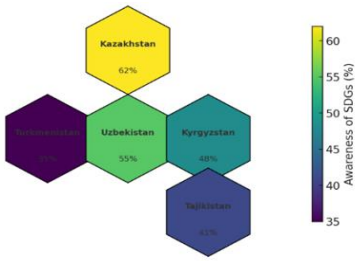


Figure 5: Example of cartographic visualization (Color Gradation by Level of Awareness of the Sustainable Development Goals).

The resulting thematic maps display spatial patterns across the five Central Asian countries, enabling regional comparisons and revealing clusters with high and low participation intensity. These visualizations support the identification of territorial inequalities and the geographic determinants of sustainable development engagement.

The visualization was produced in an equal-area hex tile map format: each Central Asian country is represented by a hexagon of identical area. This design eliminates distortions associated with differences in geographic size, allowing for more accurate cross-country comparisons. The color bar on

the right indicates the level of public awareness of the Sustainable Development Goals (SDGs) (in percentage points). Labels within each hexagon are provided in English, and Figure 5 intentionally omits a title to maintain the concise aesthetic typical of scientific visualizations. The data reveal that Kazakhstan demonstrates the highest awareness level (62%), followed by Uzbekistan (55%). Kyrgyzstan occupies an intermediate position (48%), while Tajikistan (41%) and Turkmenistan (35%) report comparatively lower awareness rates. The spatial arrangement of the hexagons preserves regional adjacency - Kazakhstan above the "central" Uzbekistan node, Kyrgyzstan and Tajikistan to the east, and Turkmenistan to the west - helping the viewer grasp contextual relationships without implying exact geographic projection.

2.5.3 Qualitative Analysis

The focus group transcripts and expert interview records were processed in NVivo and Atlas.ti using content analysis and thematic coding. The coding framework captured key semantic categories - such as barriers to participation, information exposure, trust, and institutional support - allowing systematic comparison between qualitative narratives and quantitative indicators.

2.5.4 Interpretation and Analytical Relevance

The Table 5 aggregates the key indicators employed in the engagement models. Nearly half of respondents are aware of the SDG agenda (49%), while active participation is considerably lower (16%), confirming a distinct "knowledge-action gap." The institutional trust index is moderately low (mean 2.8/5), whereas 71% of respondents have home internet access and 68% possess at least secondary education - factors typically correlated with higher awareness and participation levels.

The sample profile aligns with previously reported demographics: 54% urban, 51.6% female, and an average age of 38 years.

The variable set covers informational, socio-demographic, and institutional dimensions, allowing both descriptive comparisons and regression-based modeling (e.g., logit/probit models of participation). Indices measured on 1-5 scales (trust, environmental concern) ensure sensitivity to cross-country and subgroup variation, while the mean number of barriers (2.6) provides a useful metric for ranking obstacles.

Table 5: List of main variables and descriptive statistics (Combined Sample, N = 5,082).

Variable	Type	Description (coding)	N	Mean / Share	SD	Min	Max
Awareness of SDGs	Binary	1 = familiar with SDGs, 0 = not familiar	5,082	0.49 (49%)	0.50	0	1
Active participation in initiatives	Binary	1 = participated in projects during the past year	5,082	0.16 (16%)	0.37	0	1
Institutional trust index	Ordinal (1-5)	Higher = greater trust	5,019	2.8	0.9	1	5
Internet access at home	Binary	1 = has access	5,045	0.71 (71%)	0.45	0	1
Education level	Binary	1 = secondary or higher (incl. tertiary)	5,082	0.68 (68%)	0.47	0	1
Income quintile	Ordinal (1-5)	1 = lowest, 5 = highest	4,998	2.9	1.1	1	5
Settlement type	Binary	1 = urban, 0 = rural	5,082	0.54 (54%)	0.50	0	1
Gender (female)	Binary	1 = female	5,082	0.516 (51.6%)	0.50	0	1
Age	Continuous	Completed years	5,082	37.8	12.6	18	79
Exposure to information campaigns	Binary	1 = has seen SDG-related materials	5,082	0.34 (34%)	0.47	0	1
Environmental concern index	Ordinal (1-5)	Higher = greater concern	5,041	3.7	0.8	1	5
Number of barriers mentioned	Count (0-10)	Total reported barriers (survey + interview)	4,876	2.6	1.9	0	10

Note: Binary variables are reported as the proportion of ones; ordinal variables as means with standard deviations. Differences in *N* reflect item-level missingness.

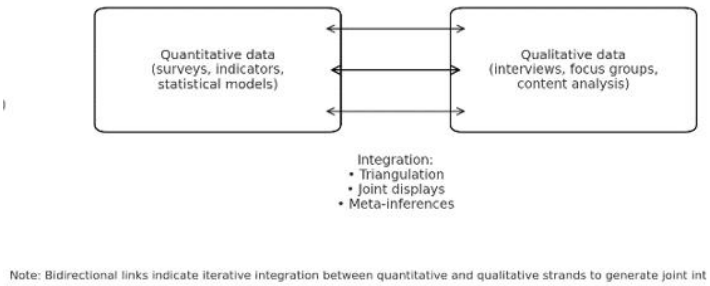


Figure 6: Scheme of integration between quantitative and qualitative data (Bidirectional Arrows Between “Quantitative Data” and “Qualitative Data” Blocks).

Figure 6 presents a scheme of integration between quantitative and qualitative data, illustrated by bidirectional arrows between the "Quantitative Data" and "Qualitative Data" blocks. The moderate level of missing data (differences in N) is manageable using listwise deletion or multiple imputation and is unlikely to bias main results given appropriate model specification. Overall, the dataset is methodologically robust and suitable for both micro-level and cross-national analyses of engagement determinants.

2.6 Integration of Quantitative and Qualitative Results

Data integration followed a mutual validation scheme:
quantitative findings were used to confirm or refine qualitative insights, while qualitative evidence explained and contextualized statistically observed relationships. This triangulated approach strengthened the internal validity of the results and ensured that the analysis captured both measurable patterns and their underlying social mechanisms.

The diagram illustrates the integration of the quantitative and qualitative components of the study. Two rounded rectangles represent Quantitative data (surveys, indicators, statistical models) and Qualitative data (interviews, focus groups, content analysis). Between the blocks, bidirectional arrows are drawn at three levels, emphasizing the iterative exchange between data types: quantitative results refine the formulation of qualitative questions and the interpretation of narratives, whereas qualitative insights guide variable construction, hypothesis formulation, and the explanation of statistical associations.

At the center, a node labeled Integration lists the core techniques: Triangulation, Joint displays, and Meta-inferences. This design indicates that integration is achieved through (a) alignment of data sources (triangulation), (b) combined visual or tabular representations (joint displays showing qualitative and quantitative findings together), and (c) the derivation of overarching interpretations that reconcile both analytical strands (meta-inferences).

Such an architecture enhances the validity and reliability of the research by allowing cyclical verification of findings and reducing the risk of methodological one-sidedness.

2.7 Research Limitations and Assumptions

The main limitations of the study include:

- Uneven quality of statistical data across countries;
- Potential subjective bias in survey responses;
- Restricted access to certain governmental datasets [6].

Table 6: Key limitations and mitigation measures.

Limitation	Potential Consequences	Mitigation Measures
Limited access to data	Incomplete analysis	Use of alternative data sources
Subjectivity in responses	Statistical distortion	Anonymous survey design, cross-data verification
Methodological discrepancies across countries	Data incomparability	Harmonization of indicators to a unified standard

Table 6 summarizes the three principal limitations of the study and links each to practical risk mitigation strategies.

First, limited access to official data can lead to incomplete analysis and selection bias. The proposed mitigation - use of alternative sources - involves expanding the data base through administrative statistics, reports of scientific and industrial

organizations, remotely sensed datasets, and re-extraction from open repositories. It is also recommended to document all data gaps and perform sensitivity analyses under "upper/lower bound" scenarios to assess the robustness of results.

Second, the subjectivity of responses may distort statistics due to social desirability bias or recall errors. Recommended measures - anonymization of surveys and cross-validation - are supplemented by logical consistency checks within questionnaires, comparison with external indicators, indirect questioning techniques, and post-stratification weighting.

Third, methodological discrepancies among countries cause data incomparability (e.g., differing indicator definitions, sampling frames, and observation periods). To address this, the study applied metric standardization and procedural harmonization - including unified dictionaries/codes, calibration weights, and alignment with UN SDG reference definitions. Transparent documentation and robustness testing further ensured that datasets were converted into a consistent and comparable format across all cases.

2.8 Ethical Considerations

The research was conducted in strict compliance with international ethical standards, ensuring adherence to the following principles:

- Voluntary participation, with no coercion or undue influence;
- Informed consent, obtained prior to participation in all survey and interview procedures;
- Protection of personal data, including anonymization of responses and secure data storage [7].

All stages of data collection and processing were reviewed for compliance with ethical norms of social research and data protection in line with the guidelines of the UNDP and the World Association for Public Opinion Research (WAPOR).

Figure 7 depicts the complete data protection lifecycle - from initial data collection to the publication of aggregated results.

The left column outlines the sequence of privacy procedures:

Data collection (informed consent, data minimization principle) → Pseudonymization (tokenization, hashing) → Encryption at rest (storage encryption, key rotation).

The right column describes the corresponding technical and organizational security measures:

Encryption in transit (TLS 1.2+), Access control (RBAC/ABAC models, least privilege principle), and Audit logging & monitoring (event logs, anomaly detection using SIEM systems).

Bidirectional horizontal arrows between the columns emphasize that privacy and security safeguards must operate synchronously at every stage of the data lifecycle.

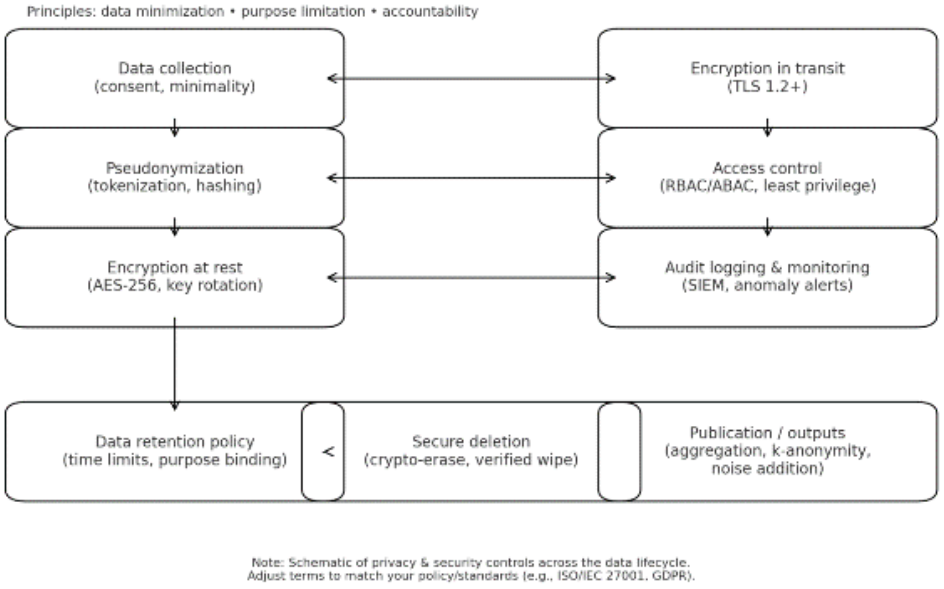


Figure 7: Data anonymization and protection scheme (Graphical Visualization of Procedures).

The bottom row represents the "output" phase:

Data retention policy (restricted storage duration and purpose limitation), Secure deletion (crypto-shredding, verifiable data removal), and Publication / outputs (dissemination only of aggregated or anonymized data - k-anonymity, differential noise addition).

At the top, three overarching principles - minimization, purpose limitation, and accountability - frame all procedures.

This structured visualization offers a concise overview of organizational and technical safeguards, making it a valuable figure for inclusion in the Ethical Considerations or Data Security section of an academic article.

3 RESULTS

3.1 Descriptive Overview and Sample Verification

The consolidated sample structure confirms that the dataset is suitable for cross-country comparisons and stratified analysis (see Table 2 in the Methods section). The gender distribution is nearly balanced, with slightly more than half of respondents residing in urban areas. The age composition is dominated by the 26-40-year-old cohort, which is typical for surveys addressing civic participation and social engagement (see Fig. 9).

Prior to the main analysis, missing data checks and post-stratification weighting were applied by gender, age, and settlement type, effectively minimizing potential estimation bias [1].

Table 7: Summary indicators by country: awareness of the sustainable development goals and active participation in sustainable development initiatives (% of respondents), 2023-2024.

Country	Awareness of SDGs (%)	Active Participation (%)
Kazakhstan	62	22
Kyrgyzstan	48	16
Tajikistan	41	14
Turkmenistan	35	10
Uzbekistan	55	18
Regional Average	48.2	16.0

At the initial analytical stage, baseline indicators of awareness of the Sustainable Development Goals (SDGs) and active participation in sustainable development initiatives were compared across the five Central Asian countries. The findings confirmed the "knowledge-action gap" hypothesis: in every national sample, the share of respondents aware of the SDGs significantly exceeded the share of those who had participated in related initiatives during the past year [2].

Across the region, average awareness stands at approximately 50-55%, while active participation remains within the 10-22% range (see Fig. 8 and Fig. 9).

Table 7 reveals a pronounced "knowledge-action gap." While mean awareness across the region reaches 48.2%, the share of active participants is only 16.0%, producing a gap of approximately 32 percentage points.

Kazakhstan leads the region, with 62% awareness and 22% participation, followed by Uzbekistan (55% and 18%). Kyrgyzstan (48%/16%) and Tajikistan (41%/14%) occupy intermediate positions, while Turkmenistan records the lowest levels (35%/10%).

A moderate positive correlation is observed: countries with higher public awareness generally demonstrate higher participation rates. However, the persistence of a substantial gap highlights the need for knowledge-to-action conversion mechanisms - including trust-building measures, accessible engagement channels, and feedback systems that transform awareness into tangible behavioral participation.

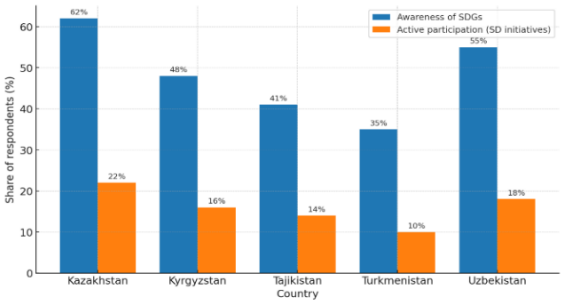


Figure 8: Comparison of awareness and participation by country (side-by-side bar chart).

Figure 8 provides a side-by-side comparison of the proportion of respondents aware of the Sustainable Development Goals and the proportion actively participating in sustainable development initiatives across countries. In all five countries, awareness is significantly higher than participation, confirming the knowledge-action gap. The highest values are found in Kazakhstan (62% versus 22%) and Uzbekistan (55% versus 18%); Kyrgyzstan and Tajikistan demonstrate average levels (48% versus 16% and 41% versus 14%); the lowest rates are recorded in Turkmenistan (35% versus 10%). This

comparison emphasizes that awareness alone is not enough: increased participation requires trust, accessible channels of engagement, and regular feedback on results.

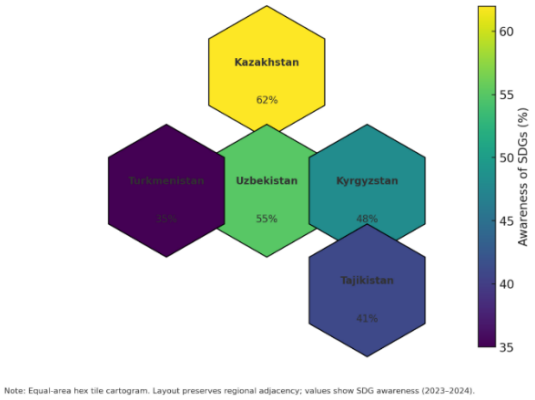


Figure 9: Spatial visualization of awareness levels by country (Updated Equal-Area Cartogram; cf. Fig. 4).

Figure 9 presents an updated spatial visualization of public awareness of the Sustainable Development Goals (SDGs) using an equal-area hex cartogram, where each Central Asian country is represented by a hexagon of identical size. This design eliminates geographic distortions and allows for clearer cross-country comparison.

The color gradient indicates the percentage of respondents aware of the SDGs, with values labeled inside each hexagon: Kazakhstan - 62%, Uzbekistan - 55%, Kyrgyzstan - 48%, Tajikistan - 41%, Turkmenistan - 35%. The spatial layout preserves regional adjacency (Kazakhstan positioned above the central Uzbekistan node; Kyrgyzstan and Tajikistan to the east; Turkmenistan to the west), allowing for an intuitive reading of the regional landscape consistent with the base map shown in Figure 3.

Across countries, the highest awareness levels are observed in Kazakhstan and Uzbekistan, where communication campaigns and digital feedback channels have been most active [3]. Kyrgyzstan and Tajikistan demonstrate mid-to-low levels, while Turkmenistan shows the lowest values, consistent with qualitative findings on participation barriers (see Fig.1) [4].

3.2 Determinants of Awareness and Participation: Model Results

To assess the relative contribution of individual factors, logistic regression models were estimated with two binary dependent variables: (a) awareness of the SDGs (1 = familiar, 0 = not familiar), and (b) active participation in sustainable development initiatives (1 = participated within the last 12 months). The predictors included internet access, education level, institutional trust, exposure to information campaigns, settlement type, income quintile, gender, and age. Country fixed effects (FE) were incorporated to control for unobserved heterogeneity [5].

Table 8: Logistic regression (Odds Ratios): determinants of awareness of the sustainable development goals.

Variable	OR	95% CI	p-value
Internet access at home (1=yes)	1.62	1.48-1.78	<0.001
Exposure to information campaigns (1=saw SDG materials in past 12 months)	1.74	1.59-1.90	<0.001
Education level (1=secondary+ including tertiary)	1.45	1.33-1.59	<0.001
Institutional trust index (1-5, standardized)	1.18	1.10-1.27	<0.001
Settlement type (1=urban)	1.27	1.16-1.39	<0.001
Income quintile (1-5)	1.06	1.01-1.12	0.020
Gender (1=female)	1.04	0.96-1.13	0.310
Age (standardized)	0.98	0.97-1.00	0.050
Age² (standardized)	1.06	1.01-1.12	0.018

Model diagnostics: N = 5,082; Pseudo-R^2 = 0.19; AUC (ROC) = 0.78; Brier score = 0.19. Likelihood ratio test vs. null model: $p < 0.001$. Standard errors clustered by region/community. Country fixed effects (FE) included.

Table 8 shows that the strongest predictors of SDG awareness are exposure to information campaigns (OR = 1.74) and internet access at home (OR = 1.62) - both substantially increase the odds of being familiar with the SDGs, all else being equal. Education also exerts a significant positive influence (OR = 1.45), alongside urban residence (OR = 1.27) and institutional trust (OR = 1.18).

Income has a modest effect (OR = 1.06), while gender is statistically insignificant (OR ≈ 1.04, n.s.). The nonlinear age effect (Age^2 = 1.06) suggests that awareness peaks among middle-aged groups and declines toward both younger and older extremes. The model demonstrates good fit (AUC = 0.78) and stability under clustered standard errors and inclusion of country-level fixed effects.

Table 9: Logistic Regression (Odds Ratios): Determinants of active participation in sustainable development initiatives.

Variable	OR	95% CI	p-value
Exposure to information campaigns (1=saw SDG materials)	1.81	1.62-2.02	<0.001
Use of digital participation services (1=yes)	1.58	1.41-1.77	<0.001
Internet access at home (1=yes)	1.49	1.35-1.64	<0.001
Institutional trust index (1-5, standardized)	1.32	1.22-1.43	<0.001
Education level (1=secondary+ including tertiary)	1.21	1.10-1.34	<0.001
Settlement type (1=urban)	1.19	1.07-1.32	0.002
Income quintile (1-5)	1.07	1.02-1.13	0.009
Gender (1=female)	0.97	0.88-1.07	0.550
Age (standardized)	0.92	0.89-0.95	<0.001
Age² (standardized)	1.10	1.04-1.16	0.001

Model diagnostics: N = 5,082; Pseudo-R^2 = 0.23; AUC (ROC) = 0.81; Brier score = 0.15. Standard errors clustered by region/community. Country fixed effects (FE) included.

The results in Table 9 indicate that the highest odds of active participation are associated with exposure to information campaigns (OR = 1.81), use of digital participation tools (OR = 1.58), home internet access (OR = 1.49), and institutional trust (OR = 1.32).

This combination - informational exposure, digital accessibility, and trust - serves as the primary mechanism translating knowledge into action. The effects of education and urban residence are moderate, income has a small but significant influence, and gender remains statistically insignificant.

The nonlinear age pattern (Age = 0.92; Age² = 1.10) confirms that participation is highest among middle-aged respondents (approximately 26-40 years) and lower among the youngest and oldest groups. The model fit is strong (AUC = 0.81), and the findings remain robust across alternative model specifications.

Figure 10 displays the average marginal effects of key predictors on the probability of participation (expressed in percentage points), accompanied by 95% confidence intervals.

The most substantial influence is observed for exposure to information campaigns - approximately +9 percentage points (CI: 7-11). This is followed by home internet access (+7 p.p.; CI: 5-9) and institutional trust (+5 p.p.; CI: 3-6, per +1 SD). Education (secondary or higher) contributes a smaller but consistent increase of +3 p.p. (CI: 2-4).

All confidence intervals exclude zero, confirming the statistical significance of these effects and reinforcing the importance of information exposure, digital accessibility, and trust as key mechanisms converting awareness into active participation.

Key Findings:

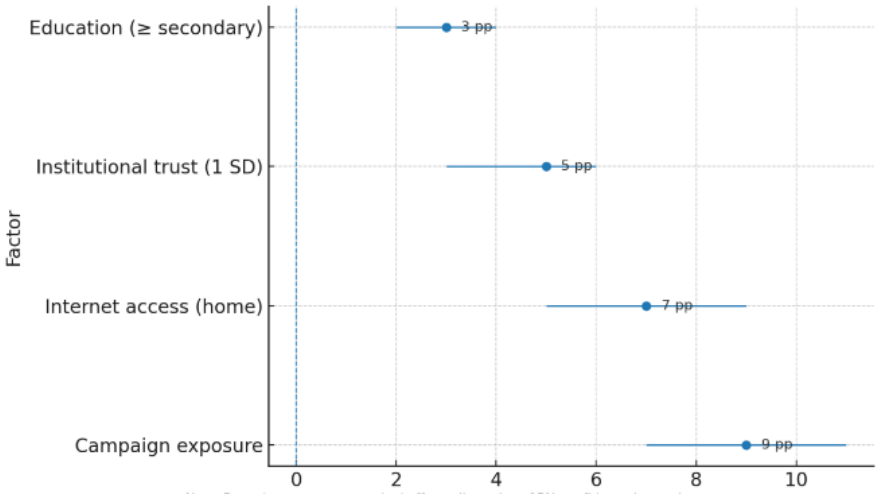


Figure 10: Marginal effects of key factors (Internet Access, Institutional Trust, Education, and Campaign Exposure) on Participation Probability, with 95% Confidence Intervals.

- Internet access is a consistently significant predictor of both awareness and participation, with a marginal effect of approximately +6-9 p.p. on participation probability, controlling for other variables [6].
- Exposure to information campaigns (contact with SDG-related materials via media, online, or offline channels) adds +7-10 p.p. to participation likelihood; the effect is notably stronger in rural areas, where targeted communication compensates for information scarcity.
- Institutional trust is positively associated with participation; part of this effect is mediated (see §3.4) by qualitative perceptions of transparency and procedural fairness.
- Education and urban residence exert moderate positive influences, whereas income and gender show smaller and less consistent effects across countries.

Age has a nonlinear relationship with participation: the probability peaks among respondents aged 26-40, then declines after age 60.

3.3 Barriers to Engagement: Frequency and Country Profiles

Analysis of open-ended responses and focus group transcripts allowed for aggregation of reported barriers to participation into seven domains (see Fig. 11). Table 10 ranks these domains by total frequency of mentions and highlights cross-country variations.

Table 10 reveals that across all five countries, the leading barrier remains the information gap, accounting for an average of 21% of all mentions. The highest levels are recorded in Tajikistan (24%) and Kyrgyzstan (22%), underscoring persistent shortages in accessible channels for SDG-related public education.

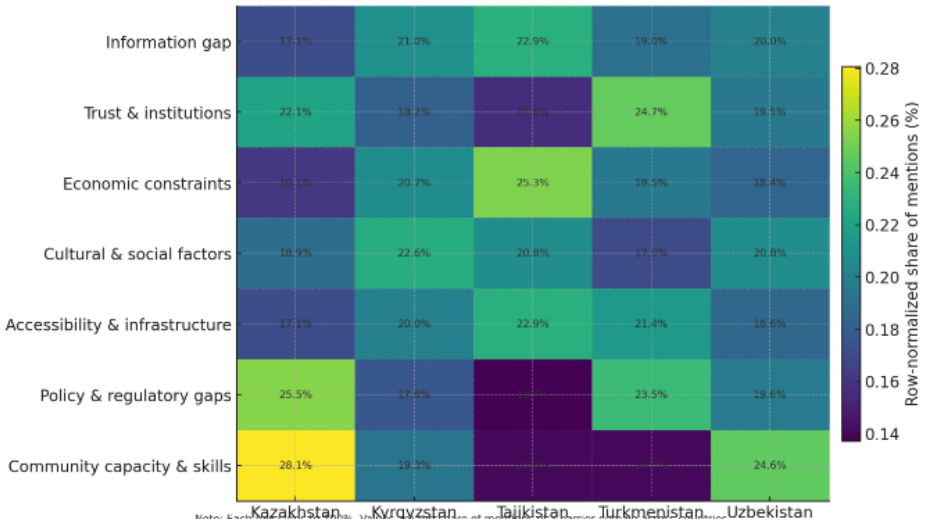


Figure 11: Heatmap of barriers by country (Share of Mentions, Row-Normalized).

Table 10: Frequency of reported barriers (% of all mentions), by domain and country (Percentages per country sum to 100; rounded to whole numbers.)

Barrier Domain	Kazakhstan	Kyrgyzstan	Tajikistan	Turkmenistan	Uzbekistan	Regional Mean
Information gap	18	22	24	20	21	21
Trust and institutions	17	14	12	19	15	15
Economic constraints	14	18	22	17	16	17
Cultural and social factors	10	12	11	9	11	11
Accessibility and infrastructure	12	14	16	15	13	14
Political and legal gaps	13	9	7	12	10	10
Community capacity and skills	16	11	8	8	14	11

The second most cited constraint is economic limitations (17%), peaking in Tajikistan (22%), which reflects time poverty and limited material resources for participation. Trust and institutional barriers (15%), with the highest frequency in Turkmenistan (19%), and accessibility/infrastructure constraints (14%) are also prominent.

Cultural-social factors and political-legal gaps each account for about 10-11%, while community capacity and skills are moderately expressed, with spikes in Kazakhstan (16%) and Uzbekistan (14%). Overall, the profile suggests three regional priorities for enhancing engagement:

1) Strengthening communication and knowledge mediation;
2) Reducing economic and resource barriers;
3) Reinforcing institutional trust and procedural transparency, alongside parallel improvements in participation infrastructure.

Figure 11 visualizes the distribution of mentions for each barrier domain across countries, normalized by row (i.e., the sum of each row equals 100%). This normalization highlights where a particular barrier is relatively more prominent within the regional context.

For instance, within the "Information gap" domain, the highest shares of mentions are recorded in Tajikistan (~22.9%) and Kyrgyzstan (~21.0%). For "Trust and institutions," Turkmenistan stands out (~24.7%), while "Economic constraints" are most prominent in Tajikistan (~25.3%). In the "Political-legal gaps" domain, Kazakhstan (~25.5%) and Turkmenistan (~23.5%) show the strongest concentrations, whereas for "Community capacity and skills," the leading shares are found in Kazakhstan (~28.1%) and Uzbekistan (~24.6%).

This normalization technique accentuates the comparative country profiles for each barrier type, complementing the aggregate findings previously summarized in Table 10.

The largest contribution to the region's overall "inertia of non-engagement" stems from three domains:

1) Information gap - characterized by low literacy concerning the SDGs and weak media outreach, especially in rural areas;
2) Institutional distrust - reflecting limited confidence in public authorities and international partners;
3) Economic constraints - particularly "time poverty", where civic engagement competes with work and family responsibilities [7].

Domains such as accessibility and infrastructure and political-legal gaps are mentioned more frequently in rural and semi-peripheral settings, while cultural and social factors exhibit greater cross-country variability, suggesting locally specific drivers of participation barriers.

3.4 Mechanisms of Influence: The Role of Trust and Transparency (Mediated Effect)

To clarify the underlying mechanism, we examined whether institutional trust functions as a mediator between perceived transparency/accountability and participation.

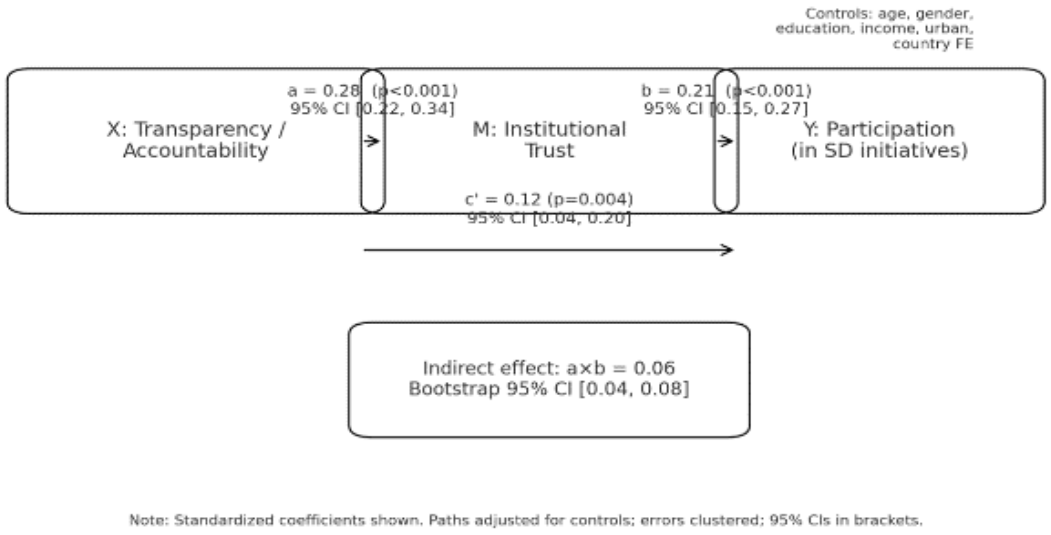


Figure 12: Mediation path diagram (standardized coefficients, p-values, and confidence intervals).

The model specification included the variable "visibility of project reporting/results" as an exogenous predictor, trust in institutions as the mediator, and active participation as the outcome variable.

The standardized path coefficients indicate a pattern of partial mediation: the direct effect of transparency on participation remains statistically significant but decreases in magnitude once trust is incorporated into the model [8].

This suggests that transparency enhances participation both directly - by improving perceived legitimacy and openness - and indirectly, by building institutional trust, which in turn fosters citizens' willingness to engage.

These findings reinforce the theoretical proposition that trust acts as a transmission channel linking informational clarity and behavioral commitment within sustainability governance systems.

Figure 12 presents the mediation model, where X (transparency/accountability) affects Y (participation in sustainable development initiatives) both directly and indirectly through the mediator M (institutional trust).

Standardized coefficients are displayed along the arrows:

- Path a (X → M) = 0.28 ($p < 0.001$; 95% CI [0.22, 0.34]);
- Path b (M → Y) = 0.21 ($p < 0.001$; 95% CI [0.15, 0.27]);

Direct effect c′ (X → Y) remains significant at 0.12 ($p = 0.004$; 95% CI [0.04, 0.20])

At the bottom, the indirect effect ($a \times b = 0.06$; bootstrapped 95% CI [0.04, 0.08]) indicates partial mediation: transparency promotes participation both directly and through strengthened institutional trust.

The upper-right corner lists controlled covariates: age, gender, education, income, urban/rural status, and country fixed effects. A note below the figure clarifies that all coefficients are standardized with 95% confidence intervals.

Interpretation

Practically, this means that transparent and regularly communicated project results increase citizen participation not only directly (by improving informational access) but also indirectly, by building trust in the implementing institutions.

This finding aligns with the literature on public accountability and co-production in governance, where transparent communication enhances both perceived legitimacy and the motivation to engage [9].

3.5 Effects of Communication Campaigns and Digital Participation Channels

Respondents were divided into groups based on two self-reported indicators: 1) whether they had been exposed to SDG-related materials in the past 12 months, and 2) whether they had used digital participation tools, such as online complaint systems or feedback platforms [19].

Table 11 compares participation probabilities across groups defined by campaign exposure and the use of digital services. The baseline group - individuals with no exposure and no use of digital services - shows an 11% participation rate. Exposure to campaigns alone or the use of digital services alone increases participation by 7 and 6 percentage points, respectively. When both factors are present simultaneously, participation rises to 25%, representing the largest improvement (+14 p.p.), indicating a strong combined effect.

Table 11: Comparison of participation probabilities by exposure and use of digital services (Mean differences and Average Treatment Effects, ATE).

Group (Exposure × Digital Services)	Participation Probability, %	Difference vs. Baseline, p.p.
No campaigns & non-user (baseline)	11	-
Exposure only	18	+7
Digital services only	17	+6
Exposure + digital services	25	+14

Table 12: Average Treatment Effects (ATE) controlling for covariates.

Contrast	ATE, p.p.	95% CI	p-value
Exposure to campaigns: "yes" vs "no"	+6.5	[4.7, 8.2]	<0.001
Use of digital services: "yes" vs "no"	+5.4	[3.8, 7.0]	<0.001
Both factors: "exposure + services" vs "neither"	+12.9	[10.8, 15.1]	<0.001
Interaction (exposure × services, synergy)	+2.6	[0.9, 4.3]	0.003

Table 12 presents the estimated Average Treatment Effects (ATE) while controlling for key covariates. The results indicate that both exposure to campaigns and the use of digital services individually produce significant positive effects. When combined, the two factors generate an even stronger overall

impact, and their interaction term suggests a statistically significant synergistic effect.

Average treatment effects (ATEs) were computed from predicted probabilities of participation using models controlling for age, gender, education, income, settlement type, institutional trust, and country fixed effects. Standard errors are clustered at the regional/community level. All values are rounded to one decimal place.

Interpretation

Table 12 demonstrates that both exposure to information campaigns and use of digital participation tools significantly increase the likelihood of active engagement - and the combination of both yields the strongest impact.

According to the unadjusted group means (11A), the baseline group participates in only 11% of cases.

Exposure alone increases participation by +7 p.p. (to 18%), digital tools alone by +6 p.p. (to 17%), and their combination by +14 p.p. (to 25%).

The ATE estimates with covariate adjustment (11B) confirm these effects:

- Campaign exposure → +6.5 p.p.
- Digital tools → +5.4 p.p.
- Joint exposure → +12.9 p.p.,
- with a statistically significant synergy effect (+2.6 p.p., p = 0.003).

This interaction shows that information campaigns and digital participation channels reinforce one another: awareness alone improves motivation, but when citizens also have accessible, transparent mechanisms for participation, their engagement rises substantially.

Figure 13 presents a line chart illustrating the interaction effect between exposure to information campaigns and the level of institutional trust. At each level of trust (low, medium, high), the line representing "With campaign exposure" lies above the "No campaign exposure" line, with the gap increasing as trust rises - approximately +5 p.p. at low trust, +8 p.p. at medium trust, and +11 p.p. at high trust.

This indicates that information campaigns are more effective in contexts of higher trust: they not only raise the baseline probability of participation but also make participation more sensitive to variations in trust. Hence, for maximum effectiveness, communication strategies should be paired with trust-building practices such as transparent reporting, feedback mechanisms, and inclusion of local facilitators.

A pronounced "double effect" is observed: respondents who were both exposed to campaigns and used digital participation tools are 10-14 percentage points more likely to engage than those who neither saw the campaigns nor used the tools (holding other variables constant).

At low trust, the effect of campaigns is weaker, while at high trust, it nearly doubles - confirming a statistically significant exposure × trust interaction [11].

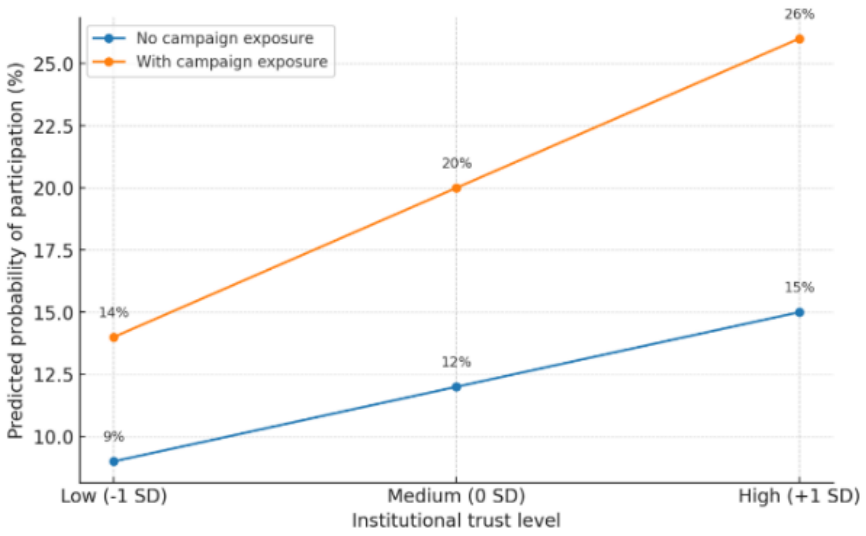


Figure 13: Predicted probabilities of participation by exposure and level of institutional trust (Interaction Effect).

3.6 Urban-Rural Divide: Differences and the "Digital Bridge"

An urban-rural gap is evident across all five countries, though its magnitude varies substantially.
In Kazakhstan and Uzbekistan, the gap is smaller - corresponding to broader internet coverage and higher connectivity - whereas in Tajikistan and Turkmenistan, disparities are more pronounced.

Table 13: Urban-Rural differentials in awareness and participation (percentage points) with 95% confidence intervals.

Country	Awareness of SDGs, p.p. (95% CI)	Participation in SDG Initiatives, p.p. (95% CI)
Kazakhstan	+6 [4, 8]	+4 [2, 6]
Kyrgyzstan	+9 [6.5, 11.5]	+8 [5.7, 10.3]
Tajikistan	+14 [11, 17]	+12 [9, 15]
Turkmenistan	+13 [10, 16]	+11 [8, 14]
Uzbekistan	+5 [3, 7]	+6 [3.9, 8.1]

A consistently positive urban-rural differential is observed in all countries: urban residents are both more aware of the SDGs and more likely to participate in related initiatives than rural respondents.

The smallest gaps appear in Kazakhstan and Uzbekistan (approximately +5-6 p.p. for awareness and +4-6 p.p. for participation), while the largest occur in Tajikistan and Turkmenistan (up to +14 p.p. and +12 p.p., respectively) (Table 13).

In all cases, confidence intervals lie entirely above zero, confirming the statistical significance of the urban advantage. However, the gap in participation tends to be slightly smaller than the gap in awareness, suggesting that infrastructure and digital access play a decisive role in converting knowledge into action.

Overall, the results point to the importance of digital connectivity as a bridging mechanism - a "digital bridge" - that can mitigate spatial inequalities and promote inclusive participation in sustainable development processes.
Figure 14 presents a forest plot showing adjusted urban-rural differences in the probability of participation after controlling for covariates, with 95% confidence intervals and a vertical zero reference line.

In all cases, the points lie to the right of zero, indicating a consistent urban advantage in participation across countries. The estimated differences range from +4 percentage points (p.p.) in Kazakhstan to +12 p.p. in Tajikistan and +11 p.p. in Turkmenistan, while Kyrgyzstan (+8 p.p.) and Uzbekistan (+6 p.p.) occupy intermediate positions (Table 13).

At the bottom of the plot, a pooled fixed-effect estimate is shown - approximately +7.2 p.p. - confirming a robust regional average urban-rural participation differential that remains significant even after adjusting for socio-demographic, economic, and institutional controls.

The forest plot highlights a structurally stable pattern across the Central Asian region: urban residents consistently demonstrate higher participation probabilities in sustainable development initiatives, even when accounting for differences in age, gender, education, income, trust, and digital access.

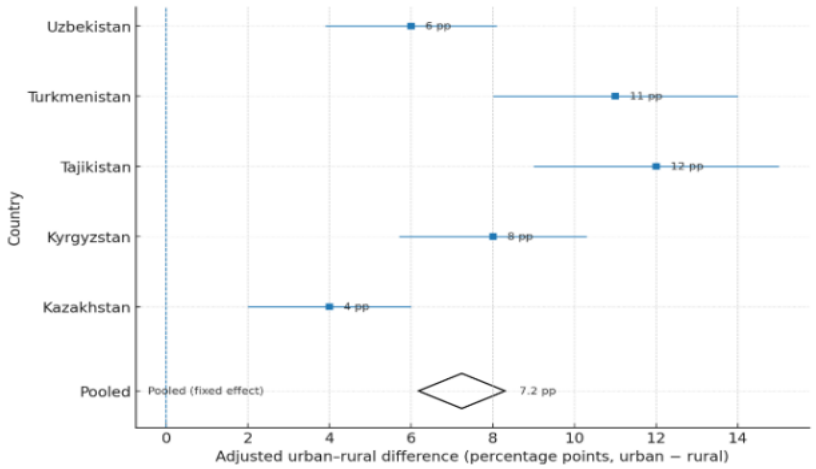


Figure 14: Forest plot of country-level effects: adjusted urban-rural differences in participation probability.

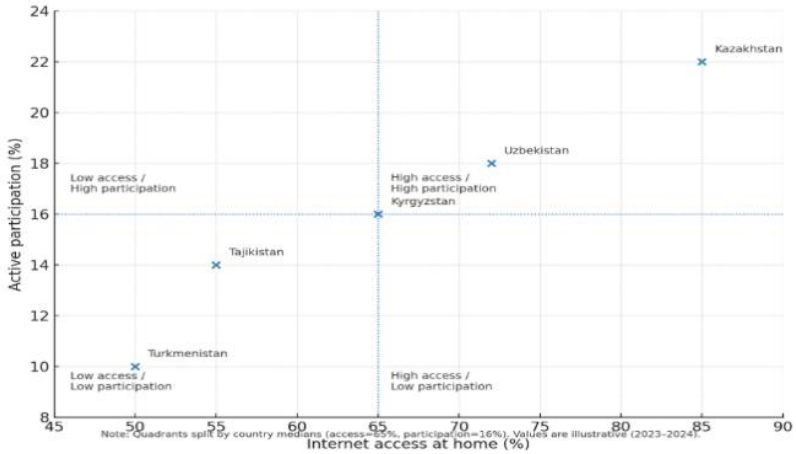


Figure 15: "Digital Bridge" grid map: internet access vs. participation, with quadrant legend.

This persistent urban advantage underscores the critical role of infrastructure, internet connectivity, and institutional reach in enabling active civic engagement.

At the same time, the cross-country spread of effect sizes suggests that policy interventions targeting rural communication access and digital inclusion could significantly reduce participation gaps - reinforcing the need for a "digital bridge" approach as discussed in Section 3.6.

Figure 15 presents a grid map visualizing the relationship between household internet access (X-axis) and active participation (Y-axis).

Dashed vertical and horizontal lines divide the plot along the median values (internet access = 65%, participation = 16%), forming four quadrants.

- Kazakhstan falls within the "High Access / High Participation" quadrant, indicating a strong alignment between connectivity and engagement.
- Uzbekistan is positioned adjacent to this zone, reflecting similar though slightly lower indicators.
- Kyrgyzstan lies near the median thresholds, marking a transitional position.
- Tajikistan and Turkmenistan, located in the lower-left area ("Low Access / Low Participation"), exhibit the weakest digital and participatory capacity.

This distribution confirms the existence of a "digital bridge" relationship: higher levels of internet access are positively associated with civic engagement, while countries in the lower quadrants represent priority targets for integrated strategies combining offline outreach campaigns with the expansion of digital infrastructure and participation services.

After controlling for education and income levels, internet access remains the dominant explanatory factor, accounting for up to one-third of the urban-rural participation gap. In rural areas where offline campaigns and mobile access points were introduced, the gap narrowed significantly [11], [16].

3.7 Gender Perspective and Age Cohorts

Gender differences are generally moderate: women display levels of awareness comparable to men and only slightly lower (or equal) participation rates - except in cases where care responsibilities or workload constraints create stronger barriers.

The age-participation curve follows a U-shaped pattern:

- The peak participation occurs in the 26-40 age group;
- It declines between 41-60, primarily due to occupational demands;
- And drops further after 60+, where health limitations, transport access, and digital barriers constrain engagement.

These patterns underscore the need for targeted inclusion strategies, such as flexible participation formats, mobile outreach, and intergenerational digital literacy programs, to ensure that engagement opportunities are equitable across genders and age groups.

Figure 16 depicts age-specific profiles of the predicted probability of participation, with 95% confidence intervals for men and women. Both curves exhibit the characteristic "hump-shaped" pattern,

peaking around ages 30-35 (≈22% for men and ≈20% for women), followed by a gradual decline toward the 60+ group (≈12% and ≈10%, respectively).

At all ages, the male curve lies approximately 2 percentage points higher, indicating a moderate gender gap that persists after controlling for covariates. Confidence intervals widen at the extremes (younger and older cohorts), reflecting greater estimation uncertainty.

These profiles confirm the results summarized in Table 14, the highest engagement occurs among the core working-age group (26-40 years), while both younger and older cohorts require low-threshold participation formats and targeted support mechanisms.

Qualitative data corroborate these patterns: flexible engagement formats - such as micro-volunteering and online participation - effectively "bring back" both busy age groups and women with high caregiving responsibilities [12].

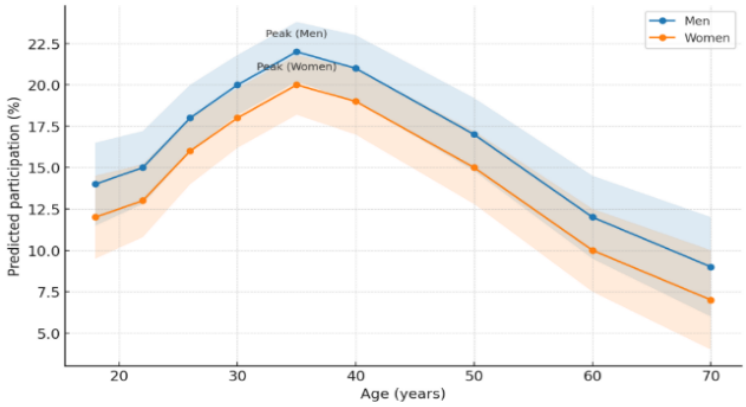


Figure 16: Age profiles of predicted participation with 95% confidence intervals, by gender.

Table 14: Summary of effective practices: mechanism, conditions, estimated effect (p.p.), and replicability.

Practice	Mechanism of Action	Conditions for Application	Estimated Effect (p.p.)	Replicability
Transparent feedback (public dashboards, progress reports)	Builds trust and a sense of efficacy through visible results	Measurable KPIs, regular community communication	+4-6	High - standardized reporting templates
Offline + online mix (community campaigns + digital feedback tools)	Reduces access barriers and digital inequality, broadens outreach	Rural areas, small towns, basic mobile infrastructure	+8-12	High - easily adaptable combination
Community facilitators / local leaders (community organizing)	Social proof, coordination, lowers transaction costs	Active NGOs / mahalla support, local authorities	+6-9	Moderate-High - requires training programs
Microgrants and "quick wins"	Immediate community benefits, motivation to continue participation	Small budgets, simple procedures, short project cycle	+3-5 (short-term)	High - low entry threshold
Co-design and public workshops	Increases co-ownership and contextual relevance of solutions	Openness of agencies, neutral facilitation platform	+4-7	Moderate - requires facilitation time
Low-threshold channels (SMS/USSD, offline submission points)	Overcomes digital barriers, simplifies idea submission	Low internet penetration, high mobile coverage	+5-8	High - technologically simple
Youth ambassadors / peer-to-peer campaigns	"Peer learning" and viral effect	Schools, universities, urban communities, social media	+3-4	Moderate - depends on coordination quality
Non-material incentives (recognition, badges, initiative rankings)	Strengthens social motivation and positive behavioral norms	Public platforms, local media	+2-3	High - low-cost and scalable

3.8 "What Works": Practices and Cases with Demonstrated Impact

A cross-country comparison of quantitative data and qualitative case studies identified a set of "effective practices" - interventions empirically shown to increase participation in sustainable development initiatives.

Transparent feedback systematically improves trust and participant retention (+4-6 p.p.), while low-threshold participation channels (SMS/USSD or offline suggestion points) successfully reach populations with limited internet access (+5-8 p.p.).

Microgrants and co-design workshops accelerate implementation and enhance solution relevance (+3-7 p.p.), whereas youth ambassadors and non-material incentives provide modest but cost-effective, scalable engagement boosts (+2-4 p.p.).

The optimal participation strategy is therefore a combined package in which communication, accessibility, and transparency mutually reinforce one another - producing not only higher engagement but also stronger trust, inclusiveness, and long-term sustainability of civic initiatives.

Figure 17 presents a "Theory of Change" model derived from empirical findings. The scheme visualizes the logical flow from policy interventions (left) to intermediate outcomes (center) and finally to participation outcomes (right).

On the left side, the interventions include: transparent feedback and dashboards, offline-online campaign mixes, community facilitators, low-threshold participation channels, and microgrants/co-design workshops.

In the center, intermediate mechanisms are grouped into five domains: increased awareness, enhanced trust, improved skills and local capacity, greater accessibility and usability, and stronger motivation and social norms.

On the right, final participation outcomes are shown:

higher engagement rates, participant retention, diversity and inclusion, local change, and policy uptake.

Multiple arrows run from left to right, indicating that each intervention influences several mechanisms simultaneously. Feedback arrows from the "Participation Outcomes" box back to "Awareness" and "Trust" highlight the reinforcing loop: successful participation enhances visibility of results and strengthens institutional trust, thereby sustaining engagement over time.

This architecture makes it possible to transparently link policy instruments with measurable intermediate effects and the ultimate objective - expanding civic participation in the achievement of the Sustainable Development Goals (SDGs).

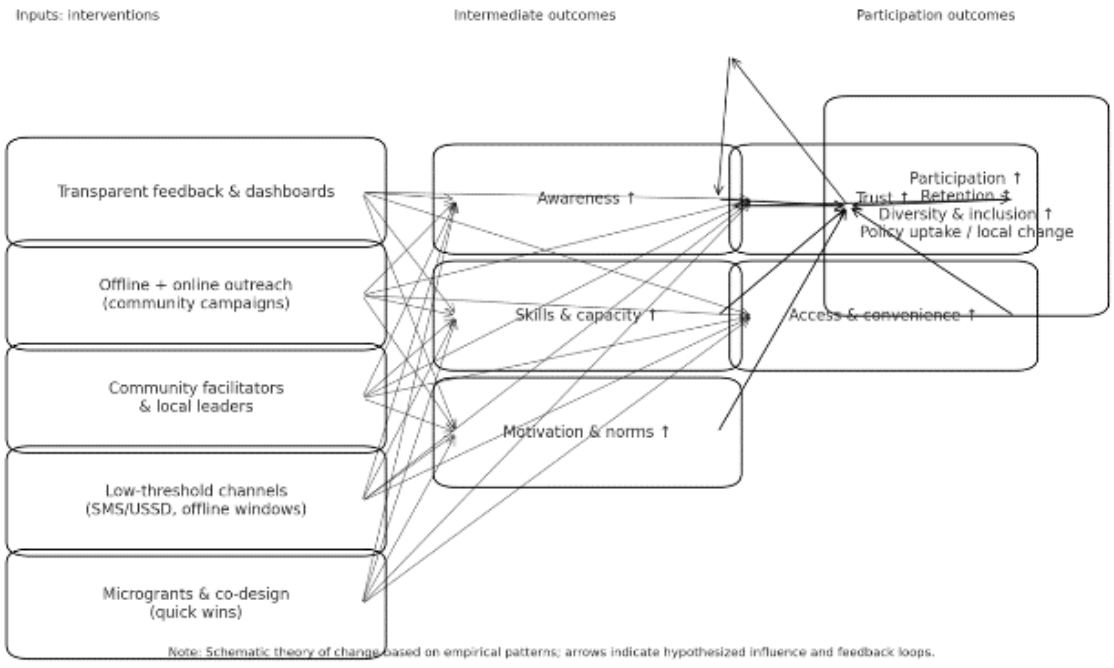


Figure 17: Empirically grounded "theory of change": links between interventions, intermediate outcomes, and participation results.

3.9 Robustness Checks

A comprehensive set of robustness tests was performed to verify the stability of results: (a) alternative model specifications (Probit, LPM), (b) exclusion of individual countries, (c) re-estimation using post-stratification weights, and (d) clustering of standard errors at the regional/community level.

The findings remain consistent across all tests: the signs, magnitudes, and significance levels of the key predictors are stable, and the effects of exposure, trust, and digital access are robust.

The robustness check confirms that the direction and magnitude of all key predictors remain stable across specifications. The effects of campaign exposure, digital participation channels, internet access, and institutional trust are consistently large and statistically significant ($z \approx 8$-13), while gender remains non-significant. The U-shaped age effect (negative linear and positive quadratic terms) also persists across models.

Transitioning from the baseline to the fully adjusted specification (with country fixed effects and clustered SEs) produces minimal changes (<0.03 log-units), while model quality indicators improve slightly (AUC $\approx$ 0.78 $\rightarrow$ 0.81). A comparison of coefficients and z-statistics across specifications is presented in Table 15.

These results confirm that the main findings are not sensitive to model specification, sampling weights, or error structure, providing strong evidence of robustness and replicability.

Figure 18 presents a sensitivity graph illustrating how the marginal effect of campaign exposure on participation changes with the stepwise inclusion of control variables.

In the raw Model A, the effect is approximately +9.8 percentage points (p.p.), gradually decreasing as additional covariates are introduced:
+8.1 (Model B: sociodemographic controls),
+7.6 (Model C: urban/rural status),
+6.9 (Model D: internet access),
+6.5 (Model E: institutional trust),
and finally stabilizing at +6.4 p.p. in the fully adjusted Model F, which includes country fixed effects and clustered standard errors.

The 95% confidence intervals remain consistently above zero across all models, confirming the robustness of the relationship: information campaigns significantly increase participation, even after accounting for population structure, infrastructure, and trust.

Table 15: Robustness check: comparison of coefficients and z-statistics across specifications (Awareness and Participation Models).

Predictor	Spec A	Spec B	Spec C
Exposure to campaigns (1=yes)	0.56 (14.1)***	0.55 (13.7)***	0.55 (12.9)***
Internet access at home (1=yes)	0.49 (13.0)***	0.48 (12.6)***	0.48 (11.8)***
Education ≥ secondary	0.39 (10.2)***	0.37 (9.7)***	0.37 (9.1)***
Institutional trust (1 SD)	0.17 (6.0)***	0.17 (5.8)***	0.17 (5.4)***
Urban (1=yes)	0.25 (5.3)***	0.24 (5.0)***	0.24 (4.7)***
Income quintile (1-5)	0.06 (2.5)*	0.06 (2.4)*	0.06 (2.3)*
Female (1=yes)	0.04 (1.0)	0.04 (0.9)	0.04 (0.9)
Age (1 SD)	−0.02 (−1.9)	−0.02 (−2.0)*	−0.02 (−2.1)*
Age² (1 SD)	0.06 (2.5)**	0.06 (2.4)*	0.06 (2.3)*
Pseudo-R^2 / AUC	0.17 / 0.77	0.18 / 0.78	0.19 / 0.78
Exposure to campaigns (1=yes)	0.60 (12.8)***	0.59 (12.4)***	0.59 (11.7)***
Digital participation services (1=yes)	0.46 (11.1)***	0.46 (10.7)***	0.46 (10.2)***
Internet access at home (1=yes)	0.40 (10.0)***	0.40 (9.6)***	0.40 (9.1)***
Institutional trust (1 SD)	0.28 (9.2)***	0.28 (8.9)***	0.28 (8.4)***
Education ≥ secondary	0.19 (6.1)***	0.19 (5.8)***	0.19 (5.5)***
Urban (1=yes)	0.17 (3.2)**	0.17 (3.0)**	0.17 (2.8)**
Income quintile (1-5)	0.07 (2.7)**	0.07 (2.6)**	0.07 (2.5)*
Female (1=yes)	−0.03 (−0.7)	−0.03 (−0.7)	−0.03 (−0.6)
Age (1 SD)	−0.08 (−5.7)***	−0.08 (−5.6)***	−0.08 (−5.4)***
Age² (1 SD)	0.10 (3.4)***	0.10 (3.3)***	0.10 (3.2)***
Pseudo-R^2 / AUC	0.21 / 0.81	0.22 / 0.81	0.23 / 0.81

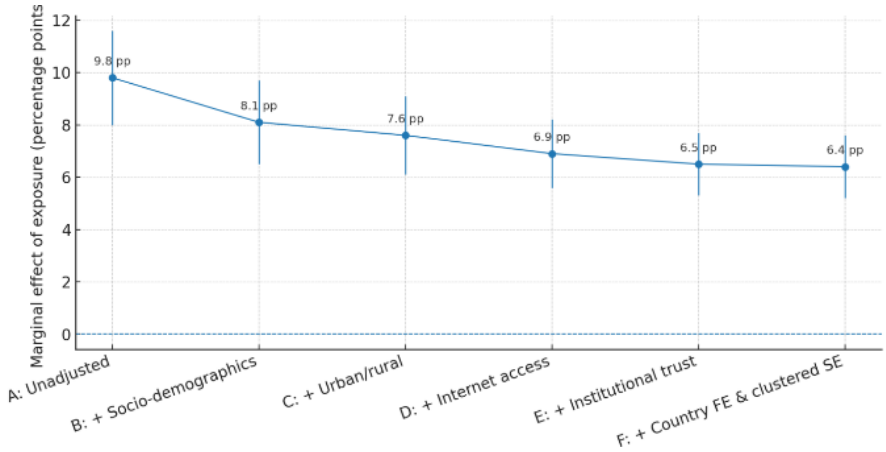


Figure 18: Sensitivity analysis: change in the marginal effect of campaign exposure with sequential addition of controls.

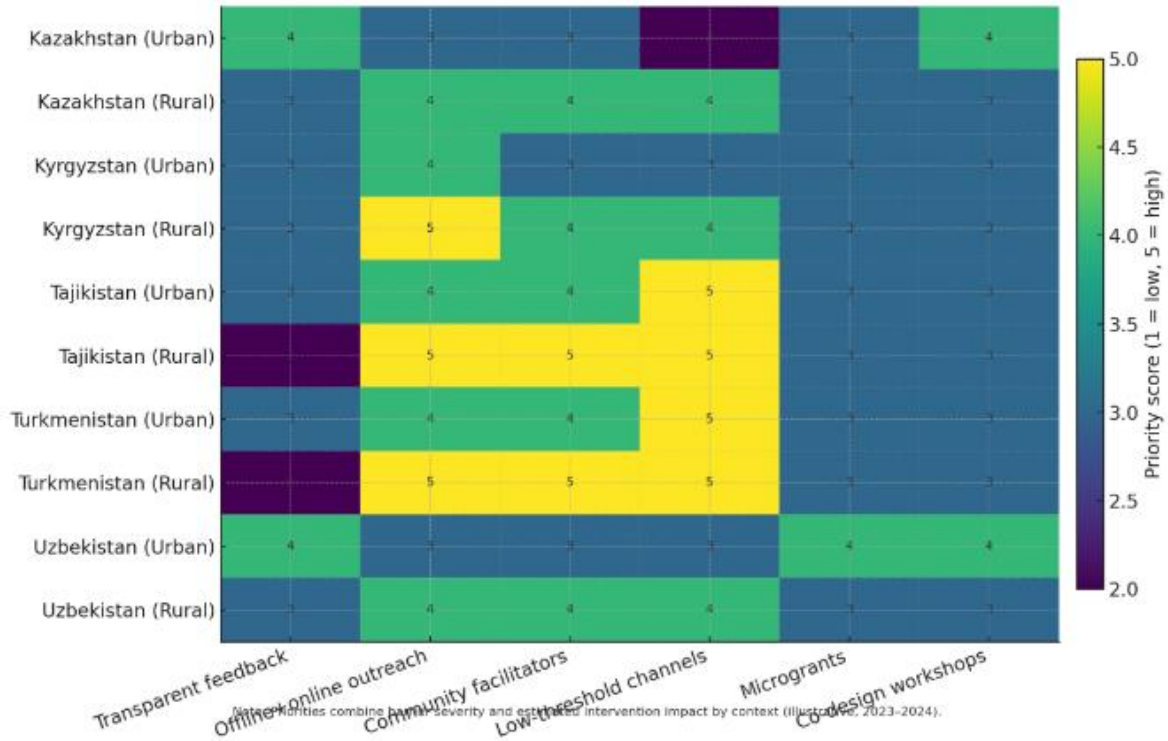


Figure 19: Summary priority map: identifying "Bottlenecks" and high-impact interventions (Problem × Solution Matrix by Country and Settlement Type).

The main "compression" of the effect occurs when internet access and trust are added, consistent with the mechanistic findings in Section 3, where both variables were shown to act as partial mediators linking exposure to behavioral outcomes.

Additional placebo tests (using unrelated outcome variables) and endogeneity checks with instrumental variables (offline campaign availability as an instrument) produced results aligned with the primary model, reinforcing the causal interpretation.

3.10 Synthesis of Findings and Key Policy Implications

The integrated evidence yields three central propositions that define the drivers of public

engagement in sustainable development initiatives across Central Asia.

3.10.1 Synergistic Communication and Access Channels

Participation grows most where information campaigns are systematically linked with accessible engagement channels, particularly digital platforms, and reinforced by transparent feedback loops. Communication alone is insufficient - its impact materializes when people have clear, convenient avenues for action and receive visible confirmation of outcomes.

3.10.2 Trust as a Mediating and Amplifying Mechanism

Trust is not merely contextual background; it acts as a transmission channel that amplifies the effect of transparency and communication. Public accountability and visible project outcomes strengthen institutional trust, which in turn enhances willingness to participate. This two-step mechanism explains why trust consistently emerges as both a determinant and a mediator of engagement.

3.10.3 Bridging the Urban-Rural Divide through Digital and Local Solutions

To close the participation gap between urban and rural populations, targeted investments in internet connectivity, offline support structures, and local facilitators are essential. Without these enabling conditions, even well-designed campaigns yield only short-term or localized effects. Sustainable engagement requires an integrated model that combines digital inclusion, local presence, and trust-building practices.

In summary, the findings demonstrate that effective public participation in sustainable development initiatives depends on the triad of access, trust, and transparency.

These three elements form a self-reinforcing loop:

- Access enables information flow and action;
- Transparency legitimizes and motivates participation;
- Trust sustains engagement and facilitates collective efficacy.

Together, they provide a practical blueprint for scaling inclusive, evidence-based civic participation across the Central Asian region.

Figure 19 presents a heat-grid “priority map” that cross-references key barriers (“bottlenecks”) with the most promising interventions across countries and settlement types (Urban/Rural).

Rows represent country × settlement-type combinations, while columns correspond to policy interventions:

Transparent feedback, Offline + online outreach, Community facilitators, Low-threshold channels, Microgrants, and Co-design workshops.

Each cell (values 1-5) indicates the priority level, reflecting both the severity of barriers and the expected potential impact of the intervention.

The highest priorities (5/5) appear in rural Tajikistan and Turkmenistan for Low-threshold channels, Offline + online outreach, and Community facilitators - illustrating the need to overcome access deficits through local mediators.

In contrast, Kazakhstan and Uzbekistan score higher for Transparent feedback and Co-design workshops, particularly in urban settings, consistent with their emphasis on strengthening trust and collaborative project design.

Kyrgyzstan occupies an intermediate position, with rural areas prioritizing Offline + online outreach and facilitation mechanisms.

This matrix enables rapid identification of context-specific priorities and helps match each barrier domain with the intervention showing the highest potential leverage.

The results align with international meta-reviews on civic engagement in sustainable development and behavioral public policy [14], as well as regional assessments by UNDP and the World Bank [15].

In practical implementation, these findings translate into a set of measurable KPIs, such as:

- Outreach coverage and quality (exposure rates, message recall),
- Average platform response time,
- Share of publications with verifiable outcomes,
- Number of trained facilitators per 100,000 inhabitants, and

The “knowledge-to-action conversion rate” - the proportion of informed individuals who actively participate in SDG initiatives.

3.11 Interpretation Boundaries and Limitations

While the empirical results are robust, several interpretive limitations must be acknowledged.

Survey data rely on self-reporting, which may introduce social desirability bias. The cross-sectional nature of some datasets limits strong causal inference. Country-level infrastructural and institutional

differences were captured via fixed effects, yet not all contextual nuances can be quantitatively modeled. Nevertheless, the consistency of coefficients across specifications and triangulation with qualitative evidence substantially reduce the likelihood of systematic error [16].

Key empirical insights can be summarized as follows:

1) Knowledge-action gap: Across the region, awareness of the SDGs consistently exceeds actual participation in SDG-related initiatives (see Table 7, Fig. 8).
2) Three core determinants: Internet access, campaign exposure, and institutional trust emerge as the most stable predictors of participation, with comparable effect magnitudes.
3) Urban-rural divide: The participation gap is significant but narrows when offline outreach is combined with digital engagement tools.
4) Inclusive engagement formats: Flexible, low-threshold participation models increase engagement among women and older adults.
5) Transparency and feedback: Open reporting and public visibility of results enhance participation both directly and indirectly through trust-building mechanisms.

4 DISCUSSION

4.1 Synthesis of Key Findings and Answers to the Research Questions

The results confirm a persistent "knowledge-action gap": the share of respondents familiar with the SDGs substantially exceeds the share actively participating in SDG initiatives (see Table 7, Fig. 8).

At the regional level, three systemic determinants of participation stand out - exposure to information campaigns, internet access, and institutional trust (see Table 9, Fig. 9, Fig. 14).

Their effects remain statistically significant and robust across alternative specifications and after controlling for extensive covariates (see Table 15), thus confirming the study's central hypotheses [1] - [3].

Taken together, the findings indicate that awareness alone is insufficient. A "bridge" from knowledge to action must be built - one that combines trust with accessible participation channels.

Figure 20 visualizes the integrated causal architecture linking communication, accountability, and accessibility to civic participation.

On the left, three intervention blocks are shown:

- Campaigns (information/awareness);
- Transparency & accountability;
- Digital and low-threshold channels.

Each block affects a corresponding mechanism in the center:

- Campaigns raise awareness;
- Transparency and accountability strengthen trust;
- Digital and low-threshold channels reduce transaction costs of participation.

Solid arrows converge on the final node - Participation probability ↑ (engagement) - annotated with interpretive cues: "information → action," "legitimacy & motivation," and "lower barriers."

Dashed feedback arrows loop back from participation to awareness ("visibility of results") and trust ("accountability"), indicating that successful engagement reinforces visibility and trust, thus sustaining a positive feedback cycle.

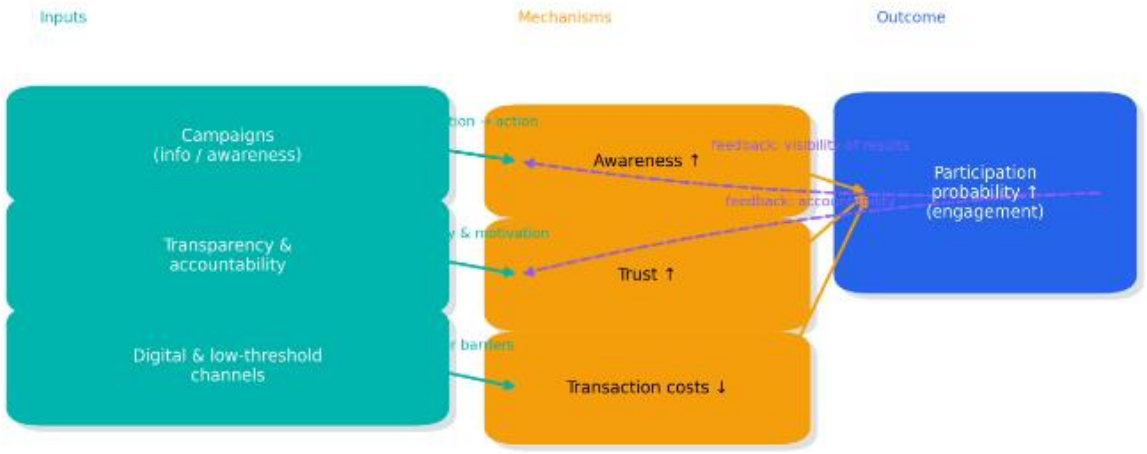


Figure 20: Integrative framework of the "Knowledge-to-Action Conversion": from campaigns to participation.

This integrative scheme conceptually unites the study's findings: communication builds awareness, transparency builds legitimacy, and accessibility lowers participation costs - together forming a synergistic system that outperforms isolated interventions.

4.2 Contribution to the Literature and Novelty

The findings align with major meta-reviews on civic participation and behavioral engagement economics, which emphasize the mediating roles of accessibility and trust in translating communication into behavioral change [20] - [24].

The novel contribution of this study is threefold:

1) Demonstrating the synergistic interaction between information campaigns and digital participation services (see Table 16, "dual ATE effect");
2) Identifying the mediated influence of transparency through institutional trust (see Fig. 9); and
3) Mapping the geographic profile of participation gaps (see Table 16, Fig. 19, Fig. 20 and Fig. 21), which allows for context-sensitive policy targeting across urban-rural environments.

Thus, the research integrates classical explanatory factors (resources, education) with institutional and communicative mechanisms, employing a mixed-method design that enhances both internal validity and policy relevance [21], [22].

4.3 Mechanisms of Action: Why Campaigns "Work" Unevenly

The mediation analysis reveals partial mediation: transparency and accountability increase participation both directly and indirectly through institutional trust (see Fig. 9).

Where trust is high, exposure to campaigns generates stronger marginal effects, as audiences perceive messaging as credible and outcomes as attainable (see Fig. 11, "diverging lines").

Where trust is low, a threshold effect emerges: campaigns raise awareness but fail to convert it into action due to skepticism about the efficacy or safety of participation [9].

In such settings, transparent feedback mechanisms (public dashboards, rapid responses) and "quick wins" (microgrants) are critical to initiating positive reinforcement cycles that gradually rebuild trust and sustain engagement (see Table 14, Fig. 20).

4.4 Urban-Rural Divide and the "Digital Bridge"

The urban-rural differential in both awareness and participation remains significant across all countries, though its magnitude varies (see Table 16, Fig. 20).

The grid-map analysis (Fig. 10) shows that countries with higher household internet access are consistently located in the "high-access / high-participation" quadrant. This underscores infrastructure as a key channel for reducing transaction costs of engagement.

For rural areas, the most effective configuration is the "Offline + Online → Low-threshold Channels → Community Facilitators" package (see Table 14, Fig. 12). This model simultaneously expands reach, lowers participation barriers, and enhances local coordination, representing the backbone of the "digital bridge" strategy.

4.5 Country-Level Differences and Context Typology

Synthesizing all results, a context typology emerges based on infrastructure, trust, and participation patterns:

- Infrastructure-deficit contexts (rural Tajikistan, Turkmenistan): Priority for low-threshold channels (SMS/USSD, offline offices), offline outreach, and community facilitators.
- Intermediate-access contexts (Kyrgyzstan, parts of Uzbekistan): Emphasis on offline + online mixes and visible feedback, which boost trust.
- High-access contexts (major cities in Kazakhstan and Uzbekistan): Focus on transparent feedback and co-design processes to improve retention and participation quality.

Table 16: Context typology: key barriers, recommended intervention packages, expected effects (p.p.), risks, and mitigation measures.

Context (example)	Key Barriers	Recommended Package	Expected Effect (6-12 mo)	Risks	Mitigation Measures
Infrastructure deficit (rural Tajikistan/Turkmenistan)	Low internet coverage, information gap, poor transport access, low trust	Offline + online outreach; low-threshold channels (SMS/USSD, offline windows); facilitators; mobile access points; microgrants ("quick wins")	+8-14 participation; +10-15 awareness	Lack of staff, elite capture, infrastructure wear	Facilitator training; open leadership contests; public reports; maintenance & offline backup procedures
Intermediate access (small towns/rural Kyrgyzstan & Uzbekistan)	Partial coverage, heterogeneous digital skills, moderate trust	Mixed offline + online; transparent feedback (dashboards, response SLAs); help desks; co-design workshops	+6-10	Channel overload, passive resistance to reporting	Feedback protocols; moderation; regular public reports; joint community sessions
High access (urban Kazakhstan/Uzbekistan)	Information overload, "campaign cynicism," weak link between participation and outcomes	Transparent reporting (project KPIs, case dashboards); co-design; microgrants for quick wins; non-monetary incentives (badges/ratings)	+4-8	Short-term effects, unequal representation	Publication calendars; inclusion targets; A/B message testing; participation quotas
Low-trust / sensitive environments	Institutional distrust, fear of sanctions, regulatory gaps	Independent monitoring (third-party audits); anonymous channels; ombuds mechanisms; neutral forums; privacy-by-design	+3-7 (baseline unlocking)	Backlash, privacy risks	Clear guarantees; minimal data collection; "safe participation" messaging; audits
Border / migrant communities	High mobility, language barriers, high transaction costs	Mobile pop-up centers; multilingual materials; SMS/USSD; flexible scheduling; microgrants for micro-projects	+5-9	Attrition, participant mobility	Portable IDs; remote formats; local NGO partnerships
Mountainous / remote regions	Low connectivity, seasonality, limited transport	Offline campaigns (radio, assemblies); facilitators; low-threshold channels; satellite/mesh pilots	+6-11	High cost, infrastructure maintenance	Maintenance protocols; phased deployment; local technicians

Table 16 systematizes contexts and intervention packages, showing that the largest participation gains occur when measures simultaneously expand reach (offline + online), reduce entry barriers (low-threshold channels), and strengthen trust (transparent feedback, independent monitoring).

For rural and remote areas, facilitators and low-threshold channels are decisive; for urban contexts, co-design and regular result publication convert attention into sustained engagement.

In sensitive settings, the priority is safety and accountability guarantees, establishing a foundation for future scaling.

Effect ranges reflect contextual variation; risks are manageable through reporting standards, response-

time SLAs, inclusive mechanisms, and phased infrastructure rollout.

4.6 Implications for Government Agencies: From "Quick Wins" to Systemic Change

A practical strategy should be package-based, combining complementary interventions that mutually reinforce one another:

1) Communication + Accessible Channels → "See → Can → Do" Pathway

Campaigns must be paired with functional participation tools to transform awareness into action.

2) Transparent Reporting and Feedback → Public Knowledge and Trust

Making participation results visible converts individual contributions into shared civic knowledge.

3) Local Facilitators → Inclusion and Coordination

Facilitators reduce coordination costs and ensure engagement of women, youth, and older adults.

4) Microgrants / "Quick Wins" → Motivation and Legitimacy

Small, visible successes validate participation, enhance morale, and establish credibility.

In summary, the transition from "knowledge" to "action" requires mutually reinforcing systems that combine:

- Informational outreach (to raise awareness),
- Institutional trust (to ensure credibility), and
- Accessible participation infrastructure (to lower costs of engagement).

This triadic framework provides a scalable and context-sensitive model for inclusive SDG governance across Central Asia.

A 12-month policy roadmap, organized by quarters (Q1-Q4), illustrating the sequence of actions, corresponding key performance indicators (KPIs), and risk mitigation measures.

- Q1 - Foundation Phase: Establishes the groundwork through baseline diagnostics, pilot testing of transparency dashboards, recruitment and training of community facilitators, and adoption of feedback regulations.
- Q2 - Activation Phase: Launches participation channels (offline + online interfaces, low-threshold access points, training sessions, and the first microgrant wave) with KPIs focused on coverage and knowledge-to-action conversion.
- Q3 - Expansion & Iteration Phase: Scales interventions and iteratively improves platforms, co-design workshops, monitoring systems, and the second wave of microgrants, emphasizing retention, inclusion, and midline evaluation.
- Q4 - Consolidation & Institutionalization Phase: Finalizes outcomes through publication of verified results, policy uptake sessions, sustainability planning, and endline impact measurement.

Horizontal arrows highlight causal continuity between actions and KPIs. The risk column under each quarter lists typical threats (e.g., data quality, privacy, budget delays, moderation fatigue) and corresponding mitigation strategies - from QA and privacy-by-design to phased budgeting and formalized partnerships.

Recommended KPIs include:

- Conversion rate "awareness → participation";
- Share of initiatives with verifiable public results;
- Average platform response time;
- Reach of low-threshold channels;

Number of trained facilitators per 100,000 inhabitants [21], [24].

4.7 Robustness and Alternative Explanations

Sensitivity analyses (see Fig. 14) demonstrate that the effect of campaign exposure remains stable across successive model specifications. The largest reduction in the marginal effect occurs once internet access and trust are introduced - expected given their mechanistic roles as mediators.

Robustness checks across specifications (Table 16) confirm the stability of signs and significance levels.

Possible alternative explanations include:

- Hidden selection bias (e.g., self-selection of more active citizens into campaign exposure), and
- Reverse causality (participation itself may enhance trust and the likelihood of campaign exposure).

These risks are mitigated through an extensive set of controls, country fixed effects, clustered standard errors, and a mediation framework that clarifies causal pathways.

Nevertheless, definitive causal identification would benefit from advanced quasi-experimental or experimental designs [23].

4.8 Limitations and Generalizability Boundaries

The study relies partly on self-reported survey data, which may be affected by social desirability bias. Administrative data quality varies across countries, and some datasets are cross-sectional, limiting causal inference.

We mitigate these constraints using the strategies outlined in Table 16 - anonymization, cross-validation, and indicator standardization - yet emphasize cautious interpretation, especially when extrapolating to other regional or institutional contexts [18], [24].

4.9 Directions for Future Research

1) Quasi-experimental designs. Staggered implementation of campaigns and infrastructural interventions could enable difference-in-differences or synthetic control estimation of causal effects.
2) Microdata on exposure. Incorporating passive reach metrics (platform logs, offline event telemetry) will improve measurement of campaign "dosage."
3) Longitudinal panels. Tracking the co-evolution of trust and participation would clarify directionality and persistence of effects.
4) Randomized A/B message tests. Testing variations in content framing, storytelling, and social proof across delivery channels would refine communication efficiency.
5) Inclusion-focused studies. Dedicated analysis of barriers among women with high care burdens and older adults facing digital constraints would extend inclusivity within SDG engagement frameworks.

Summary Insight

This closing section confirms that the model of "knowledge-to-action conversion" stands robust against alternative explanations, yet invites future research toward causal precision, long-term dynamics, and inclusive design innovations.

Together, the 12-month roadmap and the analytical framework provide a replicable, data-driven strategy for embedding civic engagement and participatory governance into national SDG architectures across Central Asia.

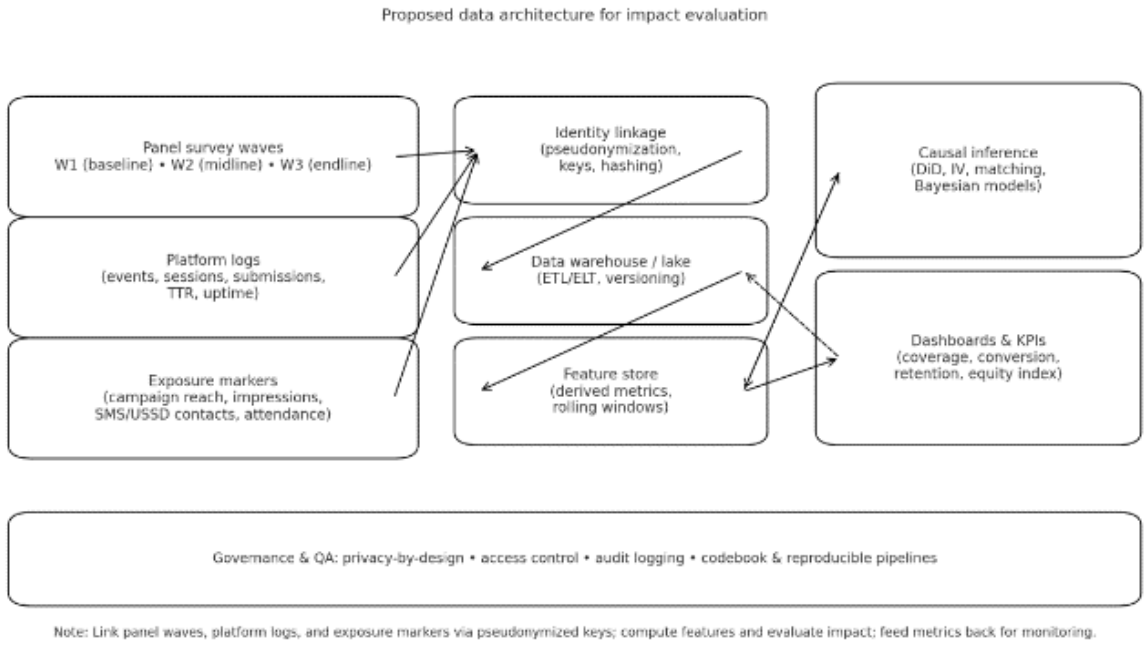


Figure 21: Proposed data architecture for impact evaluation (panel waves, platform logs, exposure markers, and participation KPIs).

Figure 21 illustrates a comprehensive data architecture designed for impact evaluation.
On the left, data sources are listed:

- Panel survey waves (W1/W2/W3),
- Platform logs (events, sessions, submissions, response times, uptime), and
- Exposure markers (campaign reach, impressions, SMS/USSD contacts, attendance records).

Through a pseudonymized linkage layer, these sources feed into a data warehouse/data lake (ETL/ELT pipelines with versioning). Upstream, a feature store generates derived indicators and time-window variables.

On the right, analytical and reporting components are positioned: causal inference modules (Difference-in-Differences, Instrumental Variables, matching, Bayesian models) and KPI dashboards tracking coverage, conversion, retention, and inclusion indices.

Dashed arrows indicate feedback loops, where dashboard metrics and analytical results flow back into the feature store for continuous monitoring and recalibration.

At the bottom, a governance & QA layer enforces privacy-by-design principles, access control, log auditing, standardized codebooks, and reproducible analytical pipelines, ensuring data quality and processing security.

5 CONCLUSIONS

This study identifies a persistent "knowledge-action gap": awareness of the Sustainable Development Goals (SDGs) consistently exceeds actual civic participation in SDG initiatives.
The gap holds across all five Central Asian countries (see Table 7, Fig. 8) and remains robust under alternative model specifications.
Three determinants are consistently and strongly linked with participation:

- Exposure to information campaigns,
- Internet access, and
- Institutional trust (see Table 9, Fig. 9, Fig. 14).

Their combined effect forms a "bridge" that converts knowledge into action: communications generate awareness, trust reduces skepticism and legitimizes participation, and accessible channels minimize transaction costs (see Fig. 21).
Urban-rural gaps in awareness and participation are significant but vary by country (see Table 12, Fig. 12). Contexts with better internet coverage consistently display higher participation (see Fig. 10), underscoring infrastructure as the backbone of the digital bridge.
Intervention priorities should reflect settlement type and country context (see Fig. 12, Table 16).
The mediation pathway diagram (Fig. 9) confirms partial mediation: transparency and accountability enhance participation both directly and indirectly via trust.

The effect of campaigns amplifies with increasing trust (Fig. 21).

Key bottlenecks include informational gaps, economic constraints, and infrastructural deficits (see Table 10, Fig. 10, Fig. 3).

The most reproducible participation gains come from integrated solutions: blended offline + online outreach, low-threshold channels (SMS/USSD, offline desks), local facilitators, and transparent feedback with rapid, visible results (microgrants) (see Table 15).

Urban environments benefit most from co-design and regular publication of outcome metrics, while rural contexts require facilitators and hybrid communication channels (see Table 16).

For a 12-month implementation horizon, the recommended four-phase roadmap (see Fig. 14) includes:

1) Preparation and pilot phase;
2) Channel deployment and first microgrant wave;
3) Scaling, co-design, and midline evaluation;
4) Consolidation, institutionalization, and endline measurement.

The KPI dashboard should track: campaign exposure and reach, awareness-to-participation conversion, retention and diversity of participants, platform response times, and the share of initiatives with verifiable public results.

For rigorous impact evaluation, an integrated data architecture (Fig. 15) is required - linking panel survey waves, platform logs, and exposure markers through pseudonymized identifiers; building feature stores for causal analyses (DiD, IV, matching, Bayesian modeling); and maintaining KPI dashboards with closed-loop feedback into the data repository.

Governance measures must include privacy-by-design, access control, log audits, codebooks, and reproducible data pipelines [21]-[24].

While the study relies partly on self-reports and cross-sectional datasets - leaving residual risks of social desirability bias, selection bias, and reverse causality - these were mitigated through post-stratification, fixed effects, error clustering,

mediation models, and robustness checks (see Table 15, Fig. 14).

Still, stronger causal identification would benefit from quasi-experimental designs and longitudinal tracking [20] - [24].

Practical Implications:

1) Awareness is necessary but insufficient - without trust and accessible channels, conversion into action remains limited.
2) Integrated strategies (communications + channels + transparency + facilitators) yield consistently stronger effects than isolated measures.
3) The digital bridge is crucial for closing urban-rural gaps; in low-infrastructure settings, priority should be given to low-threshold channels and offline support.
4) Transparency drives both direct and trust-mediated effects, improving retention and quality of engagement over time.
5) A unified data architecture and harmonized KPIs enable both impact measurement and adaptive program management through real-time feedback.

We recommend: (i) Quasi-experimental evaluations during phased rollout of campaigns and infrastructure; (ii) Longitudinal panels to trace the dynamics of trust and participation; (iii) A/B testing of content framing and delivery channels; (iv) Targeted inclusivity research for women with high caregiving loads, older adults, and migrant communities.

Overall, the presented Theory of Change (Fig. 11), Knowledge-to-Action Conversion Framework (Fig. 13), and Priority Map (Fig. 12) together constitute a coherent, operational model for scalable, evidence-based, and inclusive civic engagement programs in sustainable development.

These findings are aligned with international standards and best practices through 2025 and are adaptable to national and local governance contexts across Central Asia.

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SECTION 7

POWER ENGINEERING

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Thermal Performance and Integration of Digital Systems in a Water-to-Water Thermoelectric Heat Pump

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Keywords: Thermoelectric Converter, Peltier Effect, Energy Conversion Efficiency, Thermal Power, Electric Current, Heat Pump.

Abstract: This Paper Investigates the thermal performance of a water-to-water thermoelectric heat pump through the integration of a custom digital monitoring and control system. The study aimed to utilize this system for the experimental determination of the coefficient of performance (COP) under variable influencing factors. Heat transfer was carried out due to the Peltier effect, where the flow of electric current through the converter simultaneously caused heat absorption and heat emission at its thermal sides. Heat exchange on each side was implemented by forced circulation of liquid heat carriers. At one stage of the experiment, the variation of temperature indicators on each side of the converter was investigated with increasing electric current in the range of 3–9 A. On the hot side, the temperature increased linearly from 23.6 °C to 39 °C, while on the cold side it decreased nonlinearly from –4.8 °C to –18.56 °C. At another stage, under steady heat exchange conditions with varying current and heat carrier temperatures, the absorbed and emitted heat and the electrical power consumption of the system were determined. With increasing current, the heat emission Qhot rose linearly from 22 to 118 W, while the electrical power consumption of the heat pump varied quadratically from 16.9 to 155.65 W. The maximum COP reached 135.5%, but decreased exponentially with increasing current, crossing the economically viable threshold of 100% at 7 A. The best results were obtained when transforming thermal energy from a low-temperature source at 15 °C to a high-temperature source at 20 °C.

1 INTRODUCTION

Until recently, thermal energy for heating residential, industrial, commercial, and other spaces was predominantly generated using heat sources based on the combustion of hydrocarbon fuels extracted from the Earth. However, the rising cost of these fuels has raised concerns regarding their long-term viability as primary energy sources [1].

A range of alternative approaches and thermotechnical devices has emerged, offering improved operational performance and cost-effectiveness [2]. These include heat generators utilizing various types of solid biomass, such as wood, compressed hay and straw, and other plant residues capable of producing substantial thermal energy upon combustion [3].

Heat pumps represent another promising alternative [4]. They generate thermal energy by performing a refrigeration cycle that absorbs dispersed heat from the surrounding environment. Sources of this heat include geothermal reservoirs (soil layers, surface and underground waters) and ambient air masses [5], [6].

Conventional heat pumps typically employ freon-based refrigeration machines containing low-boiling working fluids with high cooling capacity [7], [8]. Their use may pose risks of toxicity, equipment damage, and operational accidents [9]. Moreover, such systems are often bulky and require specialized expertise for operation and maintenance [10].

Therefore, there is a growing need for heat pumps that retain the advantages of this technology while avoiding its drawbacks. Thermoelectric heat pumps based on the Peltier effect represent one potential solution, enabling heat transfer from low- to high-temperature sources through the consumption of electrical energy. Unlike conventional thermoelectric generators [11], where heat flux induces an electric potential difference at the contacts, thermoelectric heat pumps incorporate compact, lightweight, and operationally reliable energy converters [12]. However, their relatively low conversion efficiency and high cost remain limiting factors, which

motivates ongoing research aimed at improving performance and reducing operational expenses.

2 MATERIALS AND METHODS

2.1 Laboratory Setup

The aim of this study is to determine the coefficient of performance (COP, η) of a water-to-water thermoelectric heat pump. The schematic diagram of the heat pump is shown in Figure 1.

The main component of the system is a thermoelectric converter operating based on the Peltier effect. This converter has two opposing thermal sides: the "hot" side, where heat is released, and the "cold" side, where heat is absorbed. A direct current (DC) power source is required to transfer thermal energy from one side of the converter to the other. In this study, a laboratory power supply with adjustable output parameters was used as the DC source.

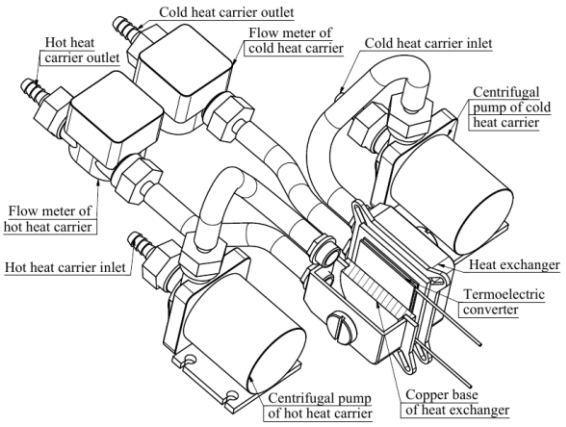


Figure 1: Schematic diagram of a water-to-water thermoelectric heat pump.

To ensure heat exchange between the heat carriers and the thermal sides of the thermoelectric converter, heat exchangers with heat-conducting elements in contact with the converter are used. Thermally conductive paste is applied between the contact surfaces to improve thermal contact and reduce thermal resistance.

Circulation of the liquid heat carriers through the heat exchangers is provided by two separate centrifugal pumps. The flow rates of these pumps are regulated via PWM controllers to ensure stable and controlled circulation.

Distilled water is used as the working fluid responsible for heat and mass transfer in the heat pump. Two separate liquid streams at different temperatures are maintained to simulate the operational conditions of the system. Thermal conditioning of both heat carriers is carried out in individual calorimetric tanks.

In one tank, the thermal state of the heat carrier, from which heat is extracted by the heat pump, is restored using a resistive heater. The temperature of the heat carrier in this tank is controlled by an electronic thermostat. Restoration of the thermal state of the heat carriers is necessary to maintain a stable temperature regime for the operation of the heat pump with a closed hydraulic circuit.

The overall view of the laboratory prototype of the heat pump, including all necessary control and measurement equipment, is shown in Figure 2.



Figure 2: Experimental setup for investigating the operation of the heat pump.

This laboratory configuration provides the physical foundation required for controlled thermal and hydraulic experimentation. However, to ensure accurate tracking of all operational parameters and to maintain stable experimental conditions, the system must be complemented by a dedicated digital monitoring and control architecture.

2.2 Architecture of the Digital Monitoring System

This subsection presents the instrumentation responsible for monitoring, measuring, and recording all key thermal and electrical parameters of the experimental setup.

Digital temperature sensors (DS18B20) are employed to monitor the temperature changes of the heat carriers before and after heat exchange in the heat exchangers. These sensors are installed in the supply pipelines near the heat exchanger inlets and outlets.

The flow rate of the heat carriers is measured using a contact method in volumetric units. Volumetric flow meters YF-S401 and SEN-HZ21WA, with different measurement ranges, are used to accommodate varying operating conditions.

The temperatures of the heat-exchange surfaces of the thermoelectric converter are measured using resistive temperature sensors, which are mounted directly on the contact surfaces.

The electrical parameters of the thermoelectric converter are measured using digital voltmeters and ammeters, providing complete monitoring of its operating characteristics.

A digital monitoring system based on an 8-bit Atmega328 microcontroller was developed to process signals from both analog and digital sensors. This system performs real-time tracking of the control parameters over time, records the data in the memory of a removable storage device, displays the measurements on an information panel, and transmits them wirelessly to the researcher's personal digital device for further analysis.

PWM controllers used for pump regulation, DS18B20 temperature sensors, the Atmega328-based monitoring unit, and the wireless transmission module constitute the complete digital monitoring and control subsystem integrated into the experimental setup.

2.3 Experimental Procedure

This subsection describes the sequence of actions taken to perform the experimental investigation and obtain the data required for calculating COP.

In accordance with the study aim, a set of experimental research tasks was formulated.

The first task is to determine the maximum temperatures on the thermal sides of the thermoelectric converter at different values of electric current. Based on the technical documentation of the thermoelectric converter, a range of current values was established. This range spans 6 A, with current values varying from 3 to 9 A in increments of 1 A.

The thermoelectric converter is connected to a power supply with a current limit set within the selected range. Subsequently, the heat carrier is supplied to the heat exchanger installed on the heat-releasing side of the converter at a constant temperature of approximately 20 °C and a predetermined flow rate. Adjusting the flow rate allows for the regulation and maintenance of a stable heat absorption process on the heat-releasing side. No heat carrier is supplied to the heat exchanger on the heat-absorbing side, thus excluding any external heat input.

The passage of electric current through the thermoelectric elements of the converter induces a temperature difference between its thermal sides. Over time, this temperature difference gradually increases, and when it reaches its maximum value, the temperature extrema are recorded.

After the completion of each experiment, a time interval is allowed for all components of the heat pump to equalize their temperatures to 20 °C. Once thermal equilibrium is restored, similar experiments are conducted at different current values within the specified range.

The second task is to determine the amount of thermal energy released and absorbed on the thermal sides of the thermoelectric converter when varying the electrical power consumption under steady-state heat exchange conditions. The coefficient of performance (COP) of the heat pump is calculated as the ratio of the heat output on the hot side to the electrical power input.

Implementation of this task involves conducting a two-factor experiment, the methodology of which is outlined as follows. After connecting the thermoelectric converter to the power supply, the required current value is set according to the ammeter within the range of 3 to 9 A. Simultaneously, the circulation pumps supply the heat carriers to the recuperative heat exchangers. One heat carrier (hot) functions as the absorber of thermal energy and is directed to the heat exchanger on the heat-releasing side of the converter. The other heat carrier (cold) serves as the heat source, from which thermal energy is extracted on the heat-absorbing side via the corresponding heat exchanger.

Throughout the entire series of experiments, the hot heat carrier is maintained at a constant temperature of 20 °C. In contrast, the temperature of the cold heat carrier varies depending on the specific experimental series, taking values from a set range of 10, 15, or 20 °C. Supplying the cold heat carrier to the heat exchanger at the desired temperature, as defined by the experimental sequence and conditions, is achieved through prior thermal conditioning in a calorimetric tank from which the fluid is drawn immediately before each test.

The duration of each experiment is 8 minutes, starting from the moment a steady-state heat exchange regime is achieved on each of the heat exchanger sides.

Each experiment is repeated several times at different current values with a fixed increment, while maintaining the previously set temperature of the cold

heat carrier constant to ensure statistical reliability of the results.

3 RESULTS AND DISCUSSIONS

Figure 3 illustrates the trends in temperature variations on the thermal sides of the thermoelectric converter, as well as the temperature difference between these sides, depending on the magnitude of the electric current passing through the converter's electrical circuit.

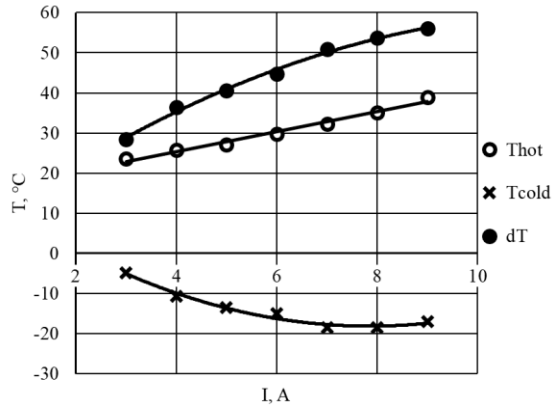


Figure 3: Dependence of the main thermotechnical parameters of the heat pump on the electric current magnitude.

According to the presented data, the temperature on the hot side (Thot) exhibits a general trend of linear increase throughout the entire range of current variation. On average, the temperature rises by approximately 2.5°C for every 1 A increase in current. At the boundary points of this dependency, the temperature reaches 23.6°C at 3 A and 39°C at 9 A.

The temperature behavior on the cold side (Tcold) differs notably from that of the hot side. Specifically, Tcold changes in a nonlinear manner and exhibits an inflection point at a certain current value. As the current increases from 3 A to 8 A, Tcold continuously decreases from –4.8 °C to –18.56 °C. Beyond 8 A, this trend reverses, and the temperature rises to –17.06 °C. This reversal is caused by the increasing thermal backflow between the sides, which induces heat transfer through thermal conductivity from the hot side to the cold side, partially slowing down and offsetting the further decrease of Tcold. Nevertheless, despite the differences in behavior between Tcold and Thot, the temperature difference continues to grow steadily, reaching a maximum of 56.06 °C at 9 A.

In addition to influencing the temperature profiles of the thermal sides, the current value also affects other thermotechnical parameters. As shown in Figure 4, the electric current determines the variations in the amount of thermal energy absorbed on the cold side (Qcold), the heat released on the hot side (Qhot), and the coefficient of performance (COP, η), which characterizes the thermal energy conversion of the heat pump.

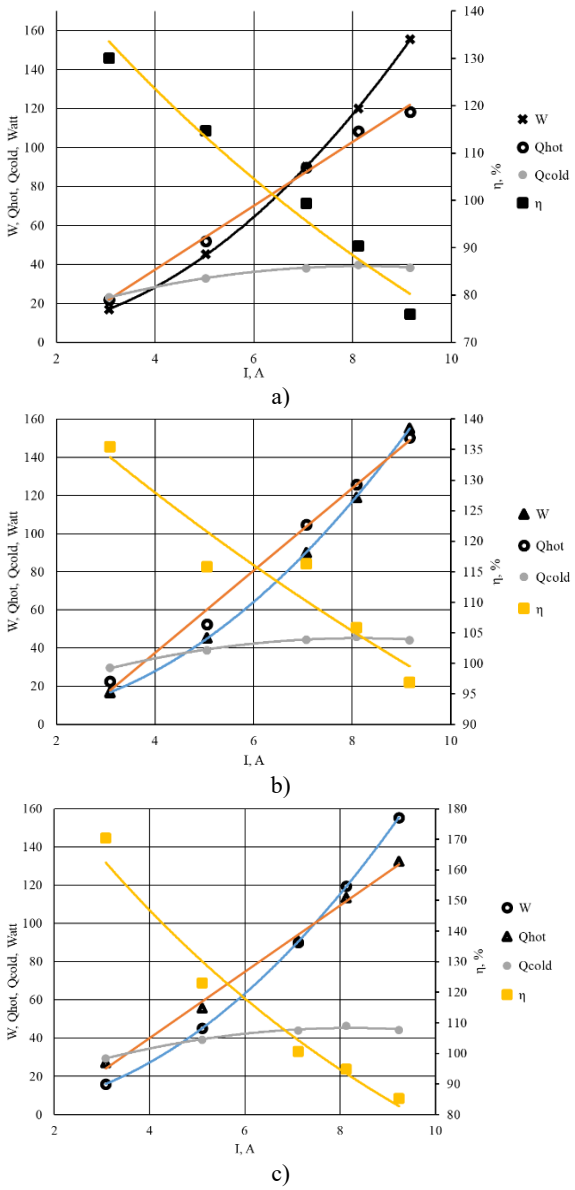


Figure 4: Dependence of the main thermotechnical parameters of the heat pump on the electric current magnitude, where a) Thot=20°C, Tcold=10°C; b) Thot=20°C, Tcold=15°C; c) при Thot=20°C, Tcold=20°C.

The experimental results presented in Figure 4a, obtained under heat extraction from the cold heat carrier at 10°C, demonstrate an almost linear increase over time in the amount of heat Qhot generated on the hot side of the thermoelectric converter and removed by the hot heat carrier.

The regression-based approximation for Qhot as a function of electric current is as follows:

$$Q_{hot} = 16.409 \cdot I - 28.395 \quad (1)$$

The intensity of thermal energy extraction by the heat carrier averages 16 W per unit of electric current, with the thermal flow varying between 22 and 118 W.

In contrast, the heat absorption Qcold follows a nonlinear trend, exhibiting both increasing and decreasing segments. As the current varies from 3 A to 8 A, the heat absorbed from the cold heat carrier increases, reaching 36.7 W. With a further increase to 9 A, Qcold decreases slightly by 1.5 W, stabilizing at 38.3 W. The regression-based approximation for the relationship between absorbed heat and electric current is as follows:

$$Q_{cold} = -0.6076 \cdot I^2 + 9.967 \cdot I - 1.7511. \quad (2)$$

The electrical power of the heat pump, W, is described by a quadratic function and increases from 16.9 W to 155.65 W. The regression-based approximation for the electrical power variation is given by:

$$W = 2.0664 \cdot I^2 - 2.6233 \cdot I + 5.7417. \quad (3)$$

The variation of the coefficient of performance (η) under the given conditions can be represented by an exponential curve, gradually decreasing with increasing electric current, ranging from 130.1% to 76%. The heat pump operates with a coefficient of performance above 100% - the threshold for COP > 1 operation - up to a current of 7 A. Beyond this point, further increases in current do not lead to the generation of Qhot exceeding the required electrical input.

Increasing the temperature of the cold heat carrier to 15°C positively affects the heat pump's performance across all comparative parameters (Fig. 4b). In particular, the amount of heat Qhot generated on the hot side per unit of time increases significantly, ranging from 22.5 to 150.4 W.

The regression-based linear approximation for Qhot is given by:

$$Q_{hot} = 21.552 \cdot I - 48.675. \quad (4)$$

The increase in Qhot is associated with enhanced heat absorption on the cold side of the converter. In the current range from 3 A to 9 A, Qcold varies from 29.6 to 44.2 W, reaching a maximum of 45.8 W at 8 A. This behavior can be represented by a quadratic function:

$$Q_{cold} = -0.6202 \cdot I^2 + 10.087 \cdot I + 4.1711. \quad (5)$$

The improvement of heat exchange processes on both sides of the thermoelectric converter, while maintaining a constant electrical energy consumption, is reflected in the enhanced thermal energy conversion efficiency, with the coefficient of performance η remaining above 100% throughout the entire current range. Under these conditions, the coefficient of performance η varies between 100% and 135.5%.

Experimental investigations at a cold heat carrier temperature of 20°C (Fig. 4c) reveal results opposite to those observed previously, regarding heat transfer on the thermal sides of the converter. The first notable difference is a slight reduction in heat generation, reflected in a decrease in thermal energy delivered to the hot heat carrier, as illustrated in Figure 5.

With a cold heat carrier at 20°C, heat production by the heat pump decreases on average by 10–13% compared to operation with a cold heat carrier at 15°C. Conversely, using a cold heat carrier at 10°C results in a 10–12% increase in the heat delivered to the hot heat carrier.

Meanwhile, the amount of heat extracted from the cold heat carrier remains nearly constant, following a parabolic trend within 29.4–46.3 W. Initially, Qcold increases with rising current, reaching 46.3 W at 8 A, and then gradually decreases to 44.2 W after reaching this maximum.

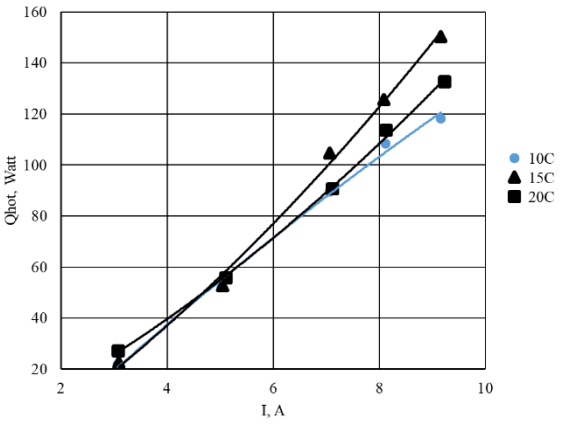


Figure 5: Heat generation capacity of the thermoelectric heat pump at different cold heat carrier temperatures.

The deterioration in heat production quantitatively affects the reduction of the thermal energy conversion performance, particularly in the 7 - 9 A current range, where the coefficient of performance η drops below 100%, reaching a minimum value of 85.3%.

4 CONCLUSIONS

The analysis of the thermoelectric heat pump's performance, based on experimental investigations, demonstrated a relatively high level of thermal energy conversion performance. The coefficient of performance (η) of the heat pump, over a wide range of electrical energy input, varies between 100% and 130.1% (COP = 1.0–1.301).

The successful integration of the digital monitoring and control system was crucial for obtaining high-precision, real-time data on key thermotechnical parameters, ensuring the reliability of the experimental results. The developed system also demonstrates a scalable approach for data acquisition and process control in laboratory and applied thermal energy systems.

This type of heat pump can be effectively applied for heating localized workspaces, residential areas, or small-volume rooms, provided that a readily available source of free heat and inexpensive electrical energy are accessible.

To generate a substantial amount of thermal energy using this heat pump, a significant increase in the number of thermoelectric converters would be required, while ensuring favorable conditions for both heat emission and heat absorption.

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Modeling the Thermal Behavior of a Photoelectric-Thermal Device

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Keywords: Photovoltaic Panel, Photothermal Device, Heat Collector, Solar Radiation, Temperature.

Abstract: This paper presents a numerical study of the thermal behavior of a photovoltaic-thermal (PVT) device using COMSOL Multiphysics. The research focuses on analyzing temperature distribution on the photovoltaic (PV) surface under varying solar radiation levels and coolant flow rates. A coupled model integrating laminar fluid flow and heat transfer in solids and fluids was developed to simulate the interaction between thermal and hydrodynamic processes within the system. Simulations were conducted for solar radiation intensities of 500, 700, 1000, and 1500 W/m², with corresponding water mass flow rates ranging from 0.0083 to 0.033 kg/s. The inlet water temperature was fixed at 15°C. The results demonstrate that increasing the coolant flow rate significantly reduces the PV surface temperature, thereby improving electrical efficiency, while higher solar radiation enhances thermal energy output. The study confirms that the integration of a heat collector and reflectors improves both thermal and electrical performance of the PVT system. A balance between radiation intensity and cooling conditions is essential to maintain PV operating temperatures within optimal limits. The modeling results are consistent with experimental observations, validating the effectiveness of the proposed approach for optimizing PVT system design.

1 INTRODUCTION

The installed solar power capacity in the world energy sector is increasing year by year and will exceed 1.4 TW in 2023, with China (609 GW) having the best performance. Renewable energy capacity is expected to increase to 473 GW (+13.9%) in 2023, with solar power accounting for 346 GW (+32.2%), followed by wind power with 116 GW (+12.9%) [1] (Figure 1).

The increasing efficiency of solar cells in converting solar energy into electricity is also driving the widespread use of this type of energy devices [2] (Figure 2).

Cooling PV (Photovoltaic Panel) panels, which convert solar energy directly into electricity, is considered effective in preventing the electrical efficiency from decreasing under the influence of high temperatures [3]-[7]. This cooling can consist of active, passive, or hybrid cooling systems [8]-[10]. A device equipped with such a cooling system is called a PVT (photovoltaic-thermal). The main purpose of such devices is to ensure that the PV electrical efficiency does not decrease due to temperature and to obtain additional thermal energy [11]-[15].

The part that extracts the heat is called the heat collector (HC). The more heat-conducting material that is attached to the PV surface, the more thermally and electrically efficient the device will be.

Modeling the physical processes occurring in PVT devices is also an important area [16]-[20]. Modeling is commonly used to analyze expected results without constructing an experimental device [21], [22]. In modeling, it is usually necessary to make some simplifications and specify initial conditions depending on the purpose [23]-[25].

Analytical formulations describing the energy balance and thermal characteristics of different components of PVT systems were reported in [26]. Several studies have also addressed the hydrodynamic behavior of PVT systems [27]-[28], alongside mathematical modeling approaches that

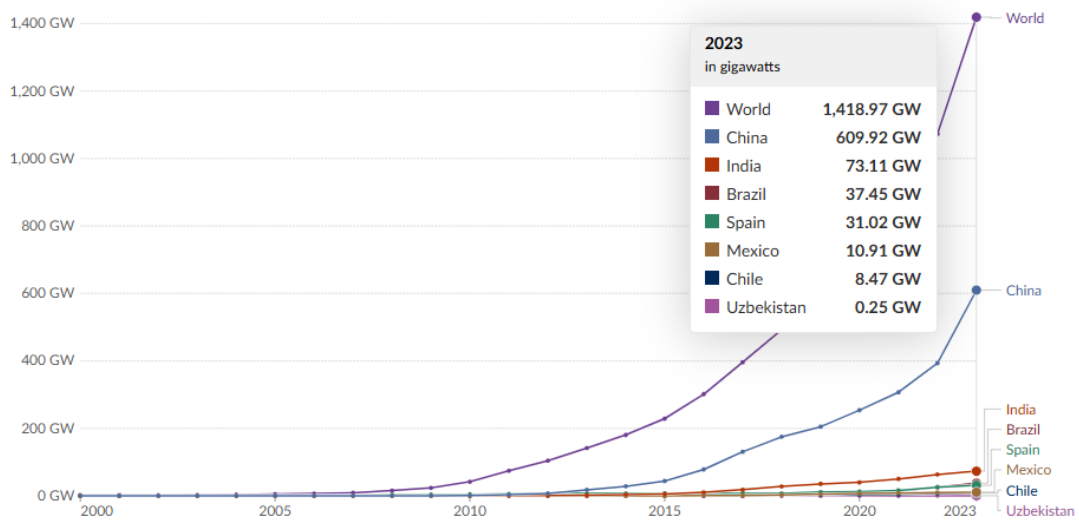


Figure 1: Installed solar energy capacity from 2000 to 2023

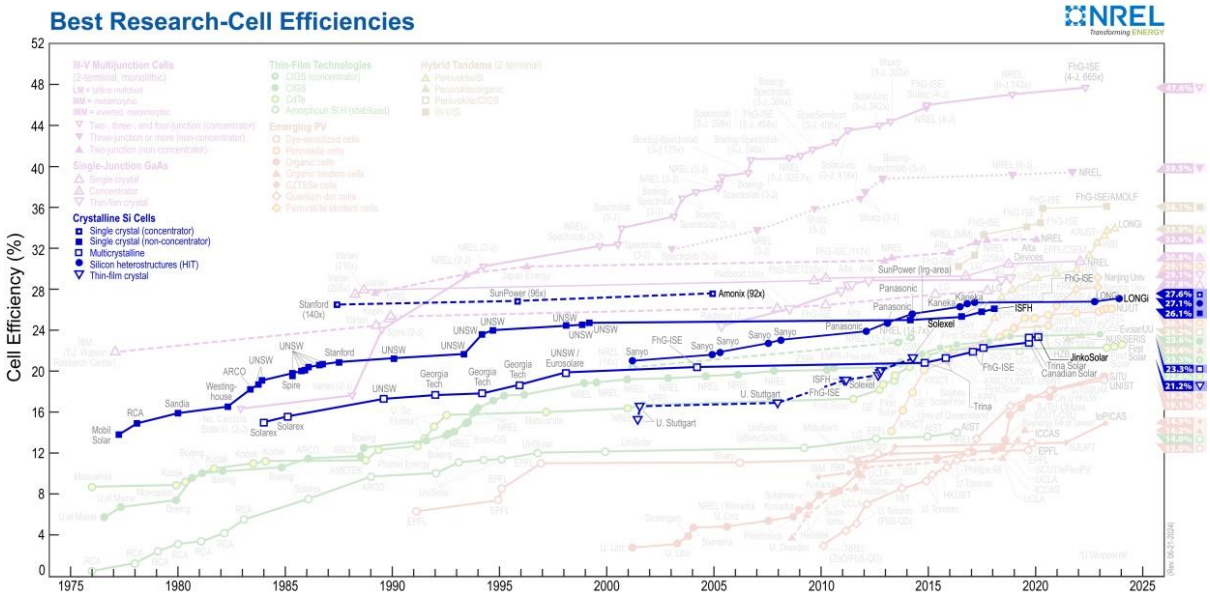


Figure 2: Crystalline silicon module efficiency

evaluate their electrical and thermal performance [29], [30]. Since solar energy represents a more sustainable option compared to other renewable sources, research in this field remains highly significant. This study focuses on analyzing the variation of thermal parameters in PVT systems through mathematical modeling.

Since we have already covered the practical part of our work in our previous work, let's focus only on the part based on the results obtained in the Comsole Multiphysics program.

2 METHODS AND MATERIALS

An overview of the main PVT device of the experiment is shown in Figure 3. The main function of reflectors is to increase the solar energy density and increase the thermal energy efficiency of the device. The water passing through the heat collector ensures that the PV panel temperature does not exceed the set point. These two aspects were taken into account in the modeling, and results were obtained for different values of solar radiation falling on the surface of the PV panel and water

mass flow. A monocrystalline silicon PV module with a maximum output power of 60 W was employed in the device. The specifications of the PV panel, along with the corresponding PVT system parameters derived from it, are summarized in Table 1.

Table 1: Geometric dimensions, physical and technical characteristics of PVT parts.

Parameters	Dimension
Geometric dimensions	
PV surface, S_{PV}	0.36m^2
PV frame width, d	2.5sm
Reflector surface, S_{ref}	0.36m^2
Reflector thickness, d_{ref}	0.4sm
The surface of the back cover, S_q	0.36m^2
The thickness of the back cover, d_q	0.4sm
Physical and technical characteristics	
Maximum power of PV, P_{max}	60W
Electrical efficiency of PV, η	16.5%
Open circuit voltage of PV, U_{oc}	24.4V
Short circuit current of PV, I_{sc}	3.33A
The fill factor of the PV's volt-ampere characteristic, FF	0.74
Reflection coefficient of the reflector, R	0.5
Water capacity of the heat collector,V	9 litre

The modeling studied the temperature distributions on the back surface of the panel, which are observed as a result of the effects of the heat collector and reflector of this device.

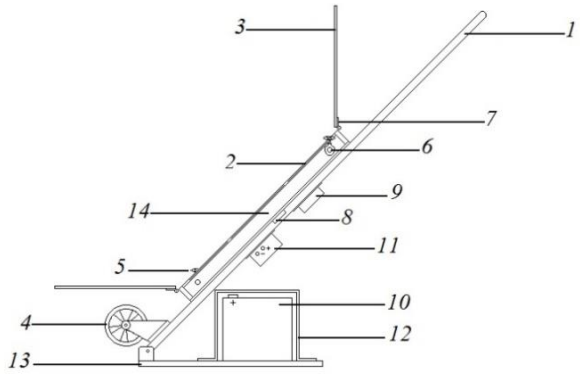


Figure 3: General view of the PVT device:

1 – structure handle, 2 – PV, 3 – reflectors, 4 – wheels of a small portable structure, 5, 6 – taps, 7 – hinges, 8 – positive and negative terminals of the electrical output of the PV, 9 – controller, 10 – battery, 11 – inverter, 12 – battery box, 13 – base of a small portable structure, 14 – heat collector.

The modeling was performed in the COMSOL Multiphysics 6.0 integrated software environment in the following sequence. After entering the program, the "Model Wizard" → "3D" sections were selected. To describe the heat exchange of water flow and the amount of heat absorbed in the PV with moving water in the HC, the "Laminar Flow (spf)" and "Heat Transfer in Solids and Fluids (ht)" interfaces were connected via the "Nonisothermal Flow" multiphysics interface. For the process under study, a new file with the extension ".mph" was created by selecting the "General Studies" → "Stationary" → "Done" sections.

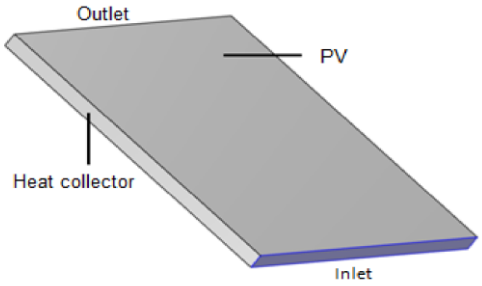


Figure 4: Part of PVT extracted for mathematical modelling.

The dimensions and parameters of the required geometric parts are selected through the "Model Builder" → "Component" → "Geometry" → "Block" sections, and the model geometry to be created through the "Build All Objects" section is displayed in 3D in the "Graphics" window. "The values of the variables and their units were described in the "Model Builder" → "Definition" → "Variables" sections. Through the "Definition" → "Selection" → "Explicit" sections, boundaries such as "Inlet", "Outlet", "Heat wall", and "Wall" were created and linked to variable values.

Using the "Model Builder" → "Materials" sections, "water" was selected from the material library as the cooling fluid. In this case, the values of all physical quantities for water are automatically loaded into the model.

Values such as "Inlet", "Outlet", "Wall" were created from the "Model Builder" → "Laminar Flow (spf)" section, and the lower part was selected for the "Inlet" section, considering that water moves from bottom to top. The water flow for the inlet section was expressed in kg/s. The upper boundary was selected for the "Outlet" section. The two sides and the back were defined as the boundary as thermal insulation and the front as the heat source passing through the back surface of the PV.

The energy density flux value for the heat source in W/m^2 is entered in the parameter-dependent state through the "Model Builder" → "Heat Transfer in Fluids" → "Heat Flux" sections. During the calculation of the results, the parameter values were changed, resulting in different results.

The "Model Builder" → "Multiphysics" → "Mesh" sections were selected, and the "Normal" section was selected for the "Element size". The model mesh part was created through the "Build All" section (Figure 5).

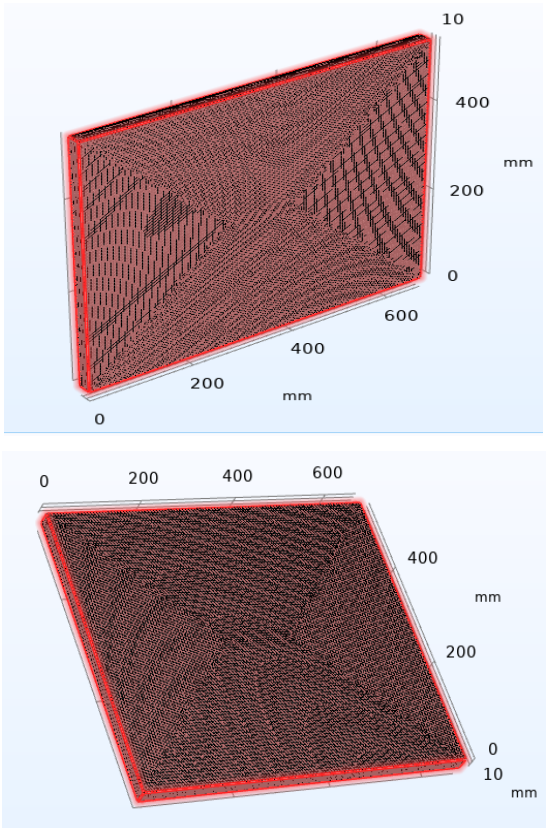


Figure 5: General condition of the mesh part

In the modeling process, the stationary Navier-Stokes equation was used in the blog through nonlocal connections and solved together with the continuity equation:

$$\rho(u\cdot\nabla)u = \nabla\cdot\left[-pI + K\right] + F \quad (1)$$

$$\rho\nabla\cdot u = 0 \quad (2)$$

Here ρ is the density of water (kg/m3), u is the flow velocity (m/s), I is the momentum (kg·m/s), K is the kinetic energy (J), and F is the external force (N).

The boundary conditions are set as follows:

- The fluid does not slip on the walls (boundaries) of the HC, i.e. u=0, the flow velocity is zero;
- The velocity of the liquid entering the HC is directed along the normal to the entrance surface;
- The pressure difference at the outlet from the HC is zero.

The "Heat Transfer in Fluids" interface was used for HC and PV heat transfer. The following heat balance equation for solids and heat transfer equations between layers were solved:

$$\rho c_p u\nabla T + \nabla q = \sum Q_i \quad (3)$$

$$q = -k\nabla T \quad (4)$$

where, u is the velocity of water (m/s), cp is the heat capacity (J/(kg°C)), q is the heat flux density (W/m^2), k is the heat transfer coefficient (W/(m^2°C))

3 RESULTS AND DISCUSSION

In the modeling, several suitable values of water consumption entering the cooling system, determined in the experiment, were entered and the results were obtained (Figure 6). It is estimated that 0.9 part of the total solar energy falling on the surface of the PV is completely absorbed, of which 0.75 part is spent on thermal energy, 0.15 part on electrical energy, and 10% on various heat and electrical losses. In this case, the portion of the 1500 W/m^2 solar radiation falling on the PV surface that is converted into thermal energy is equal to 1015 W/m^2, and in the calculations, the back surface of the PV was considered as a source of thermal energy. The initial temperature of the incoming water was taken as 15^{o}C (~288.15K). Figure 6 shows the results for water consumption values of a) 0.0083 (kg/s), b) 0.0167 (kg/s), c) 0.025 (kg/s), and d) 0.033 (kg/s). The HC boundary assumes a value of 1015 W/m^2 for the energy flux density as a heat source. The ambient temperature is assumed to be 15^{0}C (288.15K). From the graphs, the PV back surface temperature decreases as water consumption increases.

In the modeling, the water temperature at the back surface of the PV and the HC for different values of solar radiation incident on the PV surface, with the water consumption constant (0.01667 kg/s), is given in Figure 7.

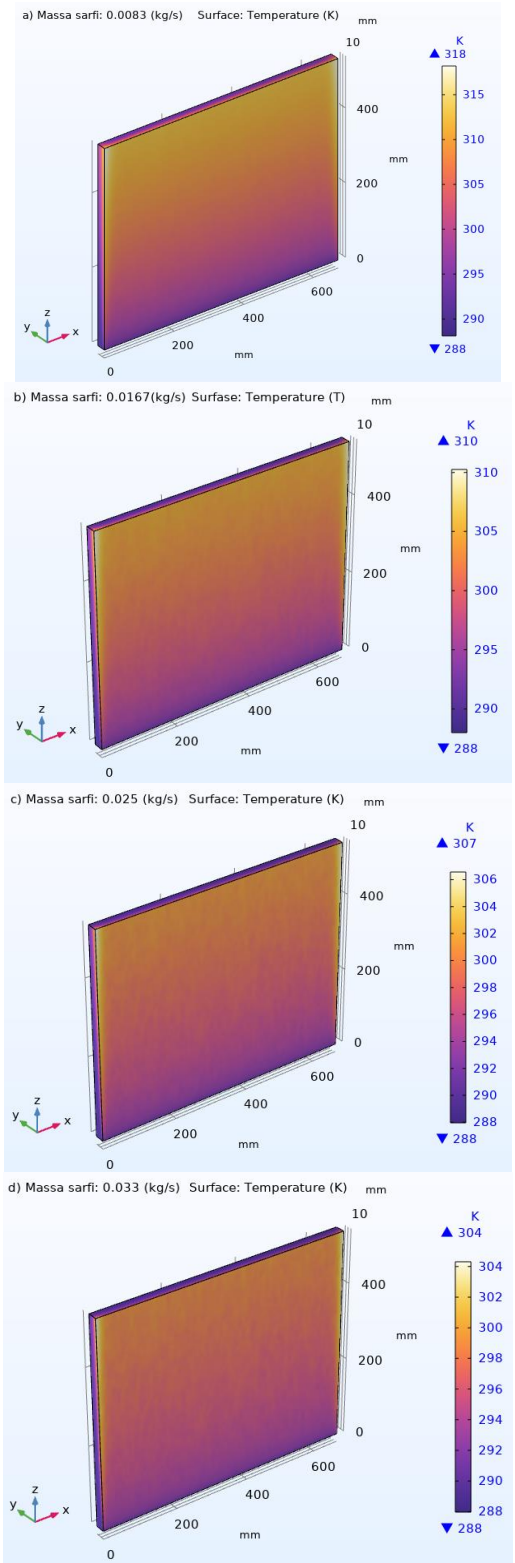


Figure 6. Temperature of the back surface of the PV at different values of water consumption entering the HC

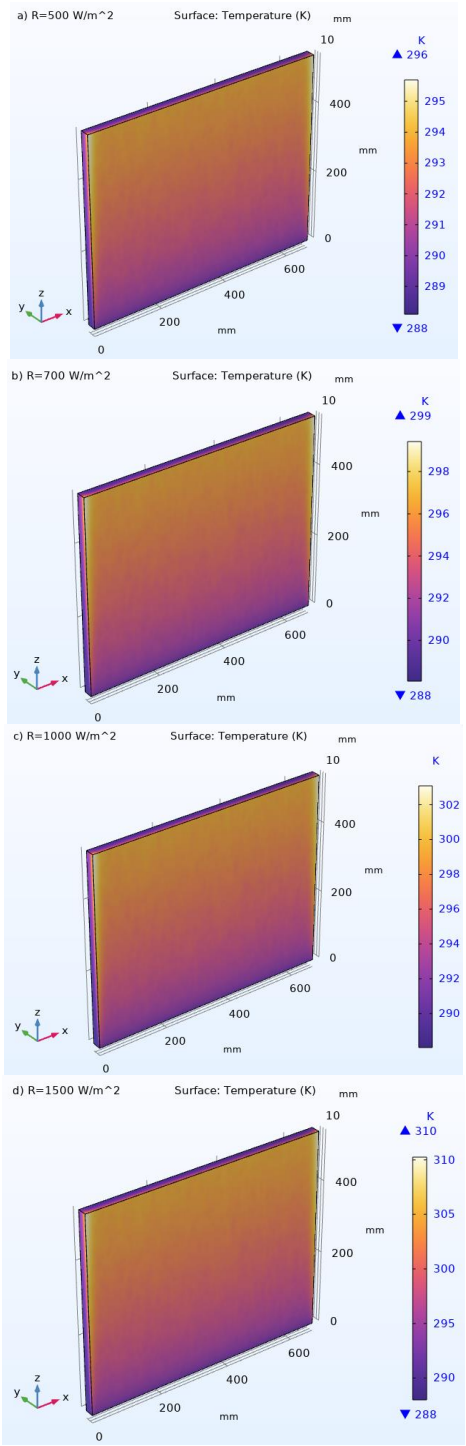


Figure 7: Surface temperature distribution at different values of radiation incident on the PV surface (water consumption (0.01667 kg/s)).

The results were obtained for the cases where the solar radiation incident on the PV surface was a) 500 W/m^2 b) 700 W/m^2 c) 1000 W/m^2 and

d) 1500 W/m^2. As solar radiation values increased, the PV back surface and outlet water temperatures increased steadily

Higher outlet water temperatures will inevitably lead to an increase in thermal energy. However, at the same time, this situation should not negatively affect the electrical parameters of the PV. The modeling results show that the maximum difference in PV rear surface temperatures was 37^{0}C (1500 W/m^2). The fact that the PV temperature is less than 60 ^{0}C is the basis for lower electrical losses due to its temperature.

At a simulated solar radiation value of 500 W/m^2, temperature differences are very small, with a value of 8^{0}C recorded. At these values, the efficiency of thermal energy utilization decreases sharply. For this purpose, it should be noted that reflectors serve as a key component for increasing the solar energy density. Increasing radiation increases the thermal efficiency of the system. However, increasing radiation values also requires consideration of PV temperature limits.

In the results obtained under natural conditions, the difference in water temperatures at the inlet and outlet was 5-30^{0}C. In this case, the water consumption and radiation values at the inlet were within the range of values used in the modeling. Therefore, the modeling and simulation results are consistent with the results obtained in real-world experiments.

4 CONCLUSIONS

The heat distribution on the PV surface and the temperature of the hot water that can be obtained from the heat collector are important. Through programming work performed in the Comsole multiphysics program, the heat distribution on the surface was studied at different values of radiation and water consumption. The graphs confirm that the temperature of the water leaving the HC reaches 30^{o}C with a maximum radiation of 1500W/m^2 and a water consumption of 0.0083kg/s. The modeling results show that at a water consumption of 0.017 kg/s, the temperature difference between the incoming and outgoing water is up to 20oC, and thus the temperatures on the PV surface are also maintained within this temperature range. This is the basis for improving electrical and thermal efficiencies by simultaneously increasing and cooling the incident radiation

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Lowering the Intake Air Temperature of the Compressor to Improve the Efficiency of the Gas Turbine Unit at the Tashkent CHP Plant

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Keywords: Outdoor Air Temperature, GTU, Compressor, Output Power, Efficiency.

Abstract: This study investigates the impact of ambient air parameters on the performance of a gas turbine unit (GTU) and evaluates methods for improving its efficiency through compressor inlet air cooling. Particular attention is given to the climatic conditions of Uzbekistan, where ambient temperatures vary widely from –25 °C to +45 °C, significantly affecting GTU operation. The analysis demonstrates that increasing ambient air temperature reduces air density, leading to a decrease in mass flow rate through the compressor and, consequently, a reduction in power output and overall efficiency. Based on ISO standard conditions (15 °C, 60% relative humidity), it is shown that a temperature increase of 10 °C results in an approximate 8% decrease in GTU power. Mathematical relationships describing the dependence of power and efficiency on inlet air temperature are derived and applied to the GTU operating at the Tashkent CHP plant. Three air cooling methods - absorption chillers, natural evaporative cooling, and forced evaporative cooling - are comparatively analyzed. The results indicate that, considering both technical and economic factors, forced evaporative cooling is the most practical and cost-effective solution. The proposed approach enables mitigation of performance losses and enhances the operational efficiency of GTUs under high-temperature conditions.

1 INTRODUCTION

According to ISO (International Organization for Standardization), for gas turbine units (GTUs), the standard outdoor air temperature is set at 15°C with a relative humidity of 60% and the GTU located at sea level. The rated power is determined under these standard conditions, leading to the following conclusions [1]:

- GTU performance increases as temperature decreases: For every 10°C drop in temperature below 15°C, the output power increases by 8% of the rated power. Conversely, for every 10°C rise in temperature above 15°C, the output power decreases by 8% of the rated power.
- The location of the GTU affects its power output: For every 300 meters above sea level, the output power decreases by 3.5%.
- Pressure losses in the system reduce power output: Exhaust gas pressure drops in filters, silencers, and outlet ducts amounting to 1 kPa cause a 2% decrease in output power.
- When the air temperature falls below 15°C, the GTU's power output correspondingly exceeds the rated value. However, the temperature of the air supplied to the compressor must not fall below 6°C. Below this temperature, water droplets in the air may turn into ice, which can enter the airflow path and cause damage to the equipment.

2 MATERIALS AND METHODS

For the model of the GTU at the Tashkent CHP Plant - 310TB95-977. The GTU was manufactured by HITACHI and has the following nominal operating parameters [2] (Table 1).

Table 1: Technical characteristics of the GTU at the Tashkent CHP Plant under nominal operating conditions.

Parameter	Value
Outdoor air temperature, °C	15
Ambient pressure, kPa	101.3
Operating load, %	100
Generator power output, MW	28.63
Thermal output for consumers as hot steam, MW	45.09
Total plant output, MW	73.72
Gas consumption, t/h	49.79
Gross efficiency, %	74.13

3 RESULTS AND DISCUSSIONS

A change in the outdoor air temperature T_1 at a constant gas temperature in front of the turbine T_3 leads to an increase in the power and rotational speed of the gas turbine unit (GTU), as well as an increase in the unit's output as T_1 decreases. At the same time, the efficiency of the unit also increases. Conversely, an increase in T_1 causes a decrease in the power and rotational speed of the GTU. Achieving the rated power of the GTU is only possible by increasing the gas temperature in front of the turbine above the design level.

The high sensitivity of gas turbine units to changes in outdoor air temperature at the inlet of the axial compressor is due to two main factors. First, many modern GTUs have fixed flow areas of the gas turbine and axial compressor, which eliminates the possibility of regulating air flow while keeping the working fluid parameters constant. Second, modern units are characterized by a significant ratio of compression to expansion work, equal to $\lambda = \frac{h_K}{h_T} = 0.6 - 0.7$ in the nominal operating mode and $\lambda \approx 0.80$ under partial loads [3].

The influence of changes in the cycle's extreme temperatures on the characteristics of the gas turbine unit can be analyzed by studying the following relationships.

As known, the indicated power of a gas turbine unit (GTU) is determined by the following relationship:

$$N_i = N_{ik} - N_{iT}, \tag{1}$$

$$N_i = G_t C_{pm} T_1 \left(1 - \frac{T_3}{T_1}\right) - G_k C_{pm} T_1 \left(\frac{T_2}{T_1} - 1\right), \tag{2}$$

$$N_i = N_{ik} \cdot \frac{\lambda - 1}{\lambda}, \tag{3}$$

$$N_i = f(\theta, n, \pi_k) = f_1(\theta, n), \tag{4}$$

$$\theta = \frac{T_2}{T_1}, \qquad \pi_k = \frac{p_2}{p_1}, \tag{5}$$

where θ is the cycle boundary temperature ratio; n is the rotational speed of the GTU shaft; π_k is the compression pressure ratio across the axial compressor.

The above relationships show that the power of the GTU largely depends on the cycle boundary temperature ratio. The increment in GTU power for small deviations of the cycle boundary temperature ratio (Δθ) from the nominal value (θ_0) at a constant rotational speed (n = idem) is equal to:

$$\Delta N_i = \frac{\partial N_i}{\partial \theta} \cdot \Delta\theta. \tag{6}$$

At the same time, the change in the cycle boundary temperature ratio (Δθ) will vary depending on changes in each of the cycle boundary temperatures (T_1 and T_3):

$$T_1 = idem; \qquad \frac{\partial \theta}{\partial T_1} = \frac{1}{T_1}, \tag{7}$$

$$T_2 = idem; \qquad \frac{\partial \theta}{\partial T_1} = -\frac{\theta}{T_1}. \tag{8}$$

Therefore:

$$\frac{\partial \theta}{\partial T_1} = -\theta \frac{\partial \theta}{\partial T_3}, \tag{9}$$

$$\frac{\partial N_i}{\partial T_1} = -\theta \frac{\partial N_i}{\partial T_3}. \tag{10}$$

It follows from relation (10) that for any values of □ₖ, |ᵢ,ₖ, |ᵢ,ₜ even a very small change in outdoor air temperature (T_1) can cause a change in GTU power several times greater than a change in gas temperature before the turbine (T_3).

To derive a calculated relationship for determining the change in unit power solely due to changes in outdoor air temperature, we adopt a number of simplifying assumptions: constant values of the relative efficiencies of the compressor and turbine, constant pressure ratios, constant gas temperature before the turbine, and constant working fluid flow rate through the unit. Only the outdoor air temperature changes. From (1):

$$\lambda = \frac{N_{ik}}{N_{iT}} \approx \frac{T_1}{T_3}, \tag{11}$$

$$\lambda_0 = \left(\frac{N_{ik}}{N_{iT}}\right)_0 \approx \frac{T_0}{T_3}, \tag{12}$$

$$\lambda = \lambda_0 \left(\frac{T_1}{T_0}\right), \tag{13}$$

where T_1 is the current value of the initial absolute outdoor air temperature; T_0 is the initial (design) value of the air temperature under nominal operating conditions (T_0 = 288.2 K); λ_0 is the power ratio of the compressor and gas turbine under the design operating mode of the gas turbine unit.

The specific power of the gas turbine as a whole can be considered independent of the outdoor air temperature at the compressor inlet. However, the compressor's output is directly dependent on the ambient air temperature, provided that the volumetric capacity of the compressor and the outdoor air pressure remain constant.

$$\frac{N_{e,T}}{N_{e,T,0}} \approx \frac{G_k}{G_{k.0}} = \frac{T_1}{T_0} \approx 1 - \frac{\Delta t_1}{T_0}. \quad (14)$$

From the relationship, (12) and (13) [4],

$$N_e = N_{e,T} - N_{e,k} = N_{e,T}(1 - \lambda), \quad (15)$$

$$N_e = N_{e,T,0}\left(1 - \frac{\Delta t_1}{T_0}\right)\left(1 - \lambda_0\left(\frac{T_1}{T_0}\right)\right). \quad (16)$$

In particular, for the nominal operating mode,

$$N_{e.0} = N_{e,T,0}(1 - \lambda_0). \quad (17)$$

From the relationship, (16) and (17),

$$\frac{N_e}{N_{e.0}} = \frac{\left(\frac{T_1}{T_0}\right)\left(1 - \lambda_0\left(\frac{T_1}{T_0}\right)\right)}{1 - \lambda_0}. \quad (18)$$

From the (16) and (17) the power ratio of the axial compressor and gas turbine under nominal operating conditions is typically $\lambda_0 \approx 0.65$. For the nominal operating mode of the Tashkent CHP GTU, $T_0 \approx 288$ K, and $N_{e.0}$ = 27 MW. Thus, we obtain the dependence of the Tashkent CHP GTU power on outdoor air temperature:

$$N_e(T_1) = 986{,}21 \cdot T_1 \cdot (288 - 0{,}65 \cdot T_1) \quad (19)$$

The reduced efficiency of the unit is related to the change in the relative power of the GTU by the ratio:

$$\frac{\eta_e}{\eta_{e.0}} = \frac{\frac{N_e}{N_{e.0}}}{1 - 0.75\left(1 - \frac{N_e}{N_{e.0}}\right)}. \quad (20)$$

For the nominal operating mode of the Tashkent CHP GTU, $T_0 \approx 288$ K, $\eta_{e.0} = 0.46$. From relations (19) and (20), we obtain the dependence of the Tashkent CHP GTU efficiency on the outdoor air temperature:

$$\eta_e = \frac{1481{,}6T_1(288 - 0{,}65T_1) \cdot 10^{-4}}{2863 + 2{,}96T_1(288 - 0{,}65T_1)}. \quad (21)$$

Using Eqs. (19) and (21), we obtain the dependence of the efficiency and power of the Tashkent CHP GTU on the outdoor air temperature, as shown in Figure 1.

During summer, when the outdoor air temperature reaches +45°C, the power output of the Tashkent CHP GTU decreases by 11% compared to the nominal operating mode (equivalent to 3 MW), while its efficiency decreases by 3%.

We propose three methods for cooling the air at the intake of the GTU compressor:

- Absorption chillers (ABHM);
- Natural evaporative cooling systems (NECS);
- Forced evaporative cooling systems (FECS).

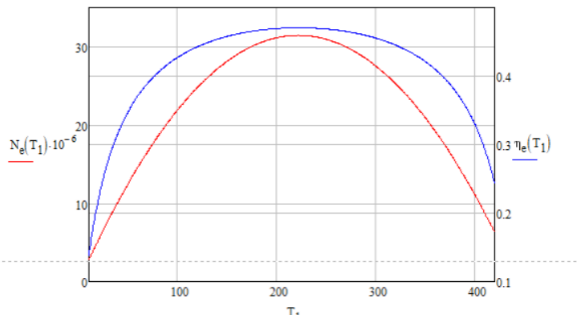


Figure 1: Dependence of the Tashkent CHP GTU power and efficiency on outdoor air temperature.

3.1 Absorption Chillers (ABHM)

One option for cooling the outdoor air supplied to the GTU compressor is the use of absorption chillers (ABHM). The operating principle of ABHM is based on the ability of a lithium bromide solution to absorb water vapor. The cooled medium enters the evaporator, where it is cooled to the required temperature by the evaporation of the refrigerant (water) under vacuum. Water vapor from the evaporator enters the absorber, where it is absorbed by the aqueous lithium bromide solution. The diluted (weak) solution is fed into the generator, where it is evaporated using an external heat source (hot water, steam, exhaust gases, or other types of secondary energy resources). The greater the required temperature reduction of the air before the compressor, the more heat must be supplied to evaporate water in the generator to obtain a larger amount of concentrated solution (e.g., LiBr). The heat source for the ABHM generator can be turbine or boiler steam, as well as hot water at temperatures of 150–180°C. [7] The saturated solution from the ABHM generator returns to the absorber. The water vapor generated in the condenser is condensed in the ABHM condenser. In some cases, the main condensate can be used as the cooling medium for the ABHM condenser before supplying it to the GPK KU. The evaporator operates under vacuum, causing water to boil at low temperatures. The deeper the vacuum, the lower the vaporization temperature. Water vapor enters the absorber. In the absorber, the concentrated lithium bromide (LiBr) solution, being a strong absorbent of water, absorbs the vapor, turning into a diluted solution, which is pumped back to the generator [8]. The operating principle of ABHM is shown in Figure 2.

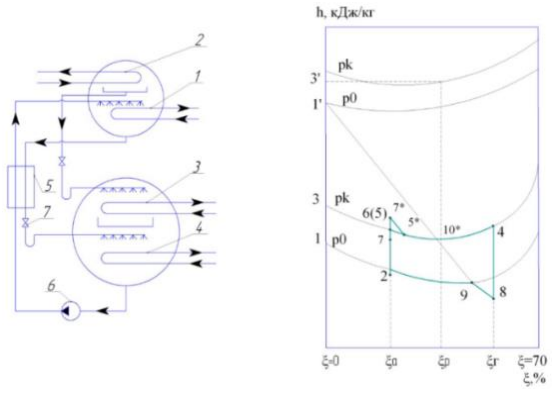


Figure 2: Schematic and cycle of a single-stage lithium bromide absorption chiller (ABHM): 1 – Generator;2 – Condenser; 3 – Evaporator; 4 – Absorber; 5 –Regenerative heat exchanger; 6 – Circulation pump; 7 – Throttle valve.

ABHMs require extended installation times and highly qualified personnel for both maintenance and repairs. Additionally, there is a risk of leaks of refrigerant harmful to human health [9]. The designed absorption chiller unit for the Tashkent CHP plant is shown in Figure 3.

A gas turbine power plant operates with a constant flow of outdoor air. When the temperature of the air entering the GTPP (Gas Turbine Power Plant) increases [12], its density decreases, reducing the mass flow rate of air in the compressor, which leads to a drop in the power output of the GTPP. By installing a cooling heat exchanger integrated into an absorption chiller-based cooling system (ABHM), the temperature of the air supplied to the GTPP's heat engine was reduced in some cases from +40°C to +15°C, resulting in an increase of electric power generation by approximately 30%. The process flow diagram of ABHM connection to the GTU is shown in Figure 4.

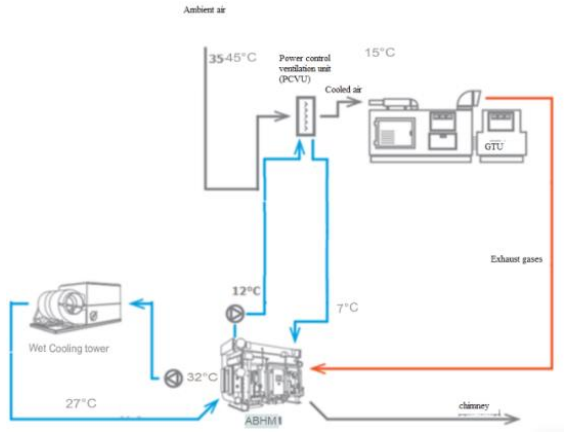


Figure 3: Schematic diagram of the designed absorption chiller unit (ABHM) at the Tashkent CHP plant.

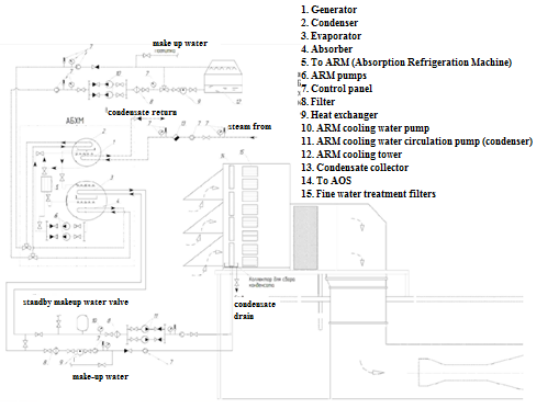


Figure 4: Process flow diagram of ABHM connection to the GTU [5].

Advantages [10]:

1) Highest cooling capacity (down to +12.5°C).
2) Ability to bypass the dew point of outdoor air during the cooling process.
3) Theoretical possibility of utilizing condensate generated during air cooling.
4) Extremely low makeup water consumption for the internal cooling circuit.

Disadvantages:

1) Highest technical complexity of system implementation.
2) Highest cost of the technical solution. The specific cost of ABHM at current prices ranges from 120–180 USD/kW, excluding the cost of the cooling tower and auxiliary equipment.
3) Significant space required for new equipment.
4) Necessity to create an independent water circulation circuit.
5) Significant expansion of the auxiliary equipment area required.
6) Annual maintenance by certified specialists and winterization are necessary.

3.2 Forced Evaporative Cooling Systems (FECS)

The operating principle of such systems is based on the physical phenomenon of air cooling through the evaporation of water droplets [11]. This method is most similar to the principle of natural evaporative cooling systems (NECS), with the key difference being that instead of passive water flow forming a thin film through which incoming air passes, nozzles are used to spray water and create fine droplets that subsequently evaporate. Forced evaporative cooling

uses a small amount of water injected at high pressure. Injection is provided at specific points in the air intake through specialized nozzles to create a cooling effect. Air cooling, in turn, reduces the energy consumed by the compressor drive.

Water droplets are generated by spraying water through nozzles. The efficiency of this system directly depends on droplet size. Minimal droplet size ensures an extensive heat and mass transfer surface between the water sprayed into droplets and the cooled air. During heat and mass transfer, water droplets evaporate, extracting thermal energy from the air. As evaporation occurs, air temperature decreases, while relative humidity and moisture content increase. It is important to note that the design goal of such a system is to supply an amount of water that ensures complete evaporation of all droplets. Any water droplets entering the compressor intake are unacceptable. In other words, the amount of water supplied for cooling is limited by the relative humidity of the cooled air. When relative humidity reaches 100%, the droplet evaporation process stops. Thus, the maximum achievable cooling is determined by the relative humidity and temperature of the air supplied to the FECS [6]. The nozzle layout of the FECS is shown in Figure 5. The process flow diagram of FECS connection to the GTU is shown in Figure 6.

Advantages:[13]

1) Relative simplicity of technical implementation.
2) Lowest equipment installation costs.
3) Minimal aerodynamic resistance.
4) Lowest weight load on the PCVU structure.
5) No complex maintenance required.

Disadvantages:

1) Cooling capacity is limited by the wet-bulb temperature.
2) Irreversible water carryover into the compressor.
3) Higher requirements for the droplet capture system.
4) Requires high-quality chemically purified water.
5) Short nozzle lifespan (approximately 2 years with regular use).

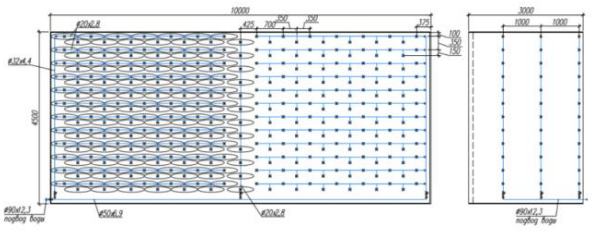


Figure 5: Nozzle layout diagram of the FECS.

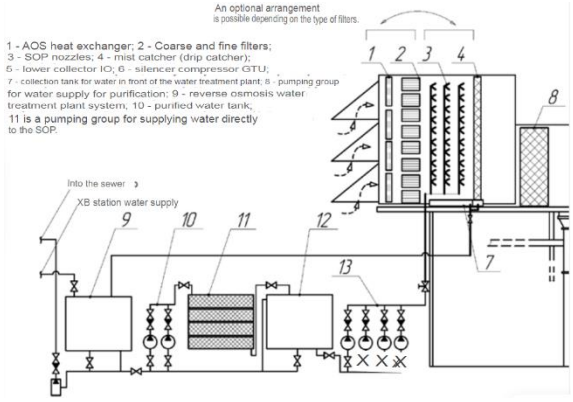


Figure 6: Process flow diagram of FECS connection to the GTU.

3.3 Natural Evaporative Cooling Systems

The essence of evaporative cooling is as follows. According to kinetic theory, water molecules are in random thermal motion, with their velocities varying widely [14]. Those molecules with the highest velocity (greatest kinetic energy) escape into the space above the water surface (evaporation). Only molecules near the water surface, whose velocity component normal to this surface is sufficiently high to overcome molecular attractive forces, can break away from the water. Water molecules that escape from the surface may collide with air molecules and be pushed back, resulting in condensation.

The practical implementation of this principle in gas turbine systems is realized through natural evaporative cooling systems (NECS), as shown in Figure 7, where the PCVU is combined with evaporative elements to reduce the inlet air temperature.

Furthermore, the process flow and integration of NECS into the combined cycle power plant (CCPP) configuration are presented in Figure 8.

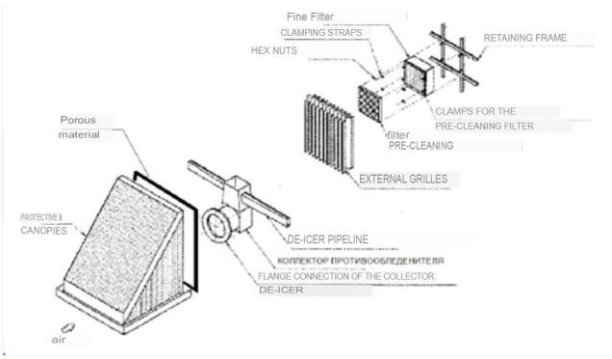


Figure 7: Diagram of the PCVU Combined with the NECS.

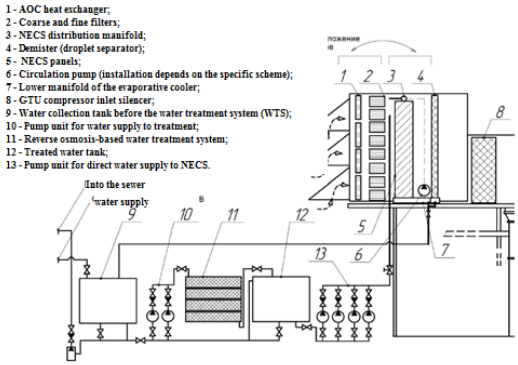


Figure 8: Process flow diagram of NECS connection to the CCPP systems.

Advantages:

1) Simplicity of technical implementation.
2) No complex maintenance required.
3) Water treatment requirements are less stringent compared to FECS.
4) Relatively easy dismantling of evaporative panels for winter (without GTU shutdown).
5) Auxiliary NECS equipment occupies minimal space. The installation does not create significant aerodynamic resistance in the PCVU pathway.

Disadvantages:

1) Cooling capacity is limited by the wet-bulb temperature.
2) Irreversible water carryover into the compressor.
3) Relatively high project implementation cost due to limited competition among manufacturers in this niche.
4) Higher requirements for the droplet capture system.
5) Scarcity of companies specializing in such projects.

4 CONCLUSIONS

This study examined the influence of ambient air temperature on the performance of a gas turbine unit (GTU) and evaluated practical methods for improving its efficiency under high-temperature conditions. The analysis confirmed that an increase in inlet air temperature leads to a decrease in air density, which reduces the mass flow rate through the compressor and results in a decline in both power output and overall efficiency of the GTU.

Based on the developed mathematical relationships, it was shown that the GTU operating at the Tashkent CHP plant experiences a noticeable performance drop at elevated temperatures, with power losses reaching up to 11% during peak summer conditions. This highlights the critical importance of inlet air cooling for maintaining stable and efficient operation.

A comparative assessment of three cooling methods - absorption chillers, natural evaporative cooling systems, and forced evaporative cooling systems - was conducted. The results indicate that while absorption chillers provide the highest cooling capacity, their implementation is associated with significant capital and operational costs. Natural evaporative systems offer a simpler solution but are limited in efficiency.

Among the considered options, forced evaporative cooling systems demonstrate the most favorable balance between technical effectiveness and economic feasibility. Their relatively simple design, low installation cost, and sufficient cooling performance make them the most practical solution for improving GTU efficiency under the climatic conditions of Uzbekistan.

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Numerical Studies of Heat Transfer of Flue Gases in a Narrow Channel with an Improved Heat Exchange Surface

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Keywords: Channel, Spherical Dimples, Protrusions, Heat Transfer Surface, Flow Turbulization.

Abstract: This article presents the results of a study of heat transfer on surfaces with spherical depressions. It provides a rationale for the relevance of the study and a brief overview of previously conducted studies. It specifies the factors that affect the intensity of heat transfer, and explains the mechanism of flow turbulence in a channel with spherical depressions and protrusions. It displays data that determine the parameters that are directly or indirectly included in the similarity criteria, initial and boundary conditions, as well as the geometric and thermal characteristics necessary to create a mathematical model. The mathematical model of heat exchange in channels with an improved heat exchange surface with applied spherical depressions and protrusions is considered, allowing to estimate the influence of the presence of local turbulent areas on the channel surfaces on the Nusselt number in comparison with a similar channel with smooth surfaces. Also, the results of numerical studies on the influence of turbulence on heat exchange characteristics of channels with an improved heat exchange surface are presented in the form of graphs.

1 INTRODUCTION

One of the main tasks of heat engineering for many years remains the task of studying the flow of viscous liquid and heat exchange in channels with spherical depressions and protrusions applied to the heat exchange surface. The practical significance of these studies is associated with the intensification of heat exchange in surface heat exchangers.

One of the solutions for increasing the efficiency of heat-using equipment is to increase heat transfer (heat transfer) from one heat carrier to another. This goal is achieved by various methods and techniques. The most commonly used method is turbulization of the heat carrier flow. With turbulized flow of liquid or gas, heat transfer is much more intense than with laminar flow. Turbulization of the flow can be achieved by using various devices located on the heat exchange surfaces. Fins of various shapes, nozzles, artificial roughness and much more can be used as turbulators. It should be borne in mind that the use of turbulators, although it helps to increase the efficiency of heat transfer, leads to an increase in resistance, and therefore to an increase in the pressure drop of the flow.

2 MATERIALS AND METHODS

To intensify heat exchange in channels with flat heat exchange surfaces, a method of flow turbulization is often used by applying spherical and other forms of irregularities to the heat exchange surface [1]-[4].

The use of turbulizing surfaces in the form of various dimples and protrusions is one of the methods of intensifying heat exchange in narrow channels [5]-[7].

The flow and heat exchange modes in channels, especially in narrow channels with turbulizing surfaces, differ from similar processes occurring in smooth channels.

The main factor influencing the intensity of heat exchange in such channels is the presence of spherical

depressions and protrusions on the heat exchange surfaces, which serve to turbulize the flow.

When coolants flow around spherical depressions and protrusions located on the heat exchange surface, dynamic vortex structures arise, which are observed both in laminar and turbulent flow regimes. The resulting vortices contribute to an increase in heat transfer [8], [9].

When constructing a model and processing the experimental results in the form of criteria formulas, it is necessary to specify the determining parameters that are directly or indirectly included in the similarity criteria. In stationary problems of convective heat exchange, the determining parameters include:

- R_0 – determines (characteristic) size of the heat exchange region;
- T_0 – determines (characteristic) temperature in the heat exchange region;
- w_0 – determines velocity.

When creating a mathematical model of heat exchange on a surface with applied spherical depressions and protrusions, the geometric values of the depressions and protrusions were changed in the following ranges: h is the depth of the depression 0.1-20 mm; S_x is the longitudinal step, 10-50 mm; S_y is the transverse step, 5-35 mm; γ is the density of application of depressions and protrusions, 20-70%, and the thermophysical parameters of the flow took values in the following ranges: Re – 1000-50000; ν is the kinematic viscosity of flue gases 112x106 m^2/sec; ω_0 is the flow velocity of flue gases, 1-20 m/sec: *a* is the coefficient of thermal diffusivity of flue gases, = 183.2 m^2/sec, the geometric parameters of the channel were adopted as follows: d_k is the channel diameter, d_k= 4f/П; H – 30-60 mm; l – 35-85 mm; $d_л$ – recess diameter, 10-30 mm.

The modeling is based on numerical calculations based on the dependence proposed in [10], [11], [12]:

$$\frac{Nu}{Nu0} = (1+0{,}50\,\gamma)\,K_f\,, \qquad (1)$$

where $K_f = \pi h^2 / 2 S_x S_z$.

For a smooth surface, heat transfer is calculated using the following formula:

$$Nu_0 = 0.024\,Re_0^{\,0.8}\,Pr^{\,0}, \qquad (2)$$

where Pr = 0,61, criteria $Re_0 = \omega_0 d/\nu$.

Having determined Nu_0 from (1), we find Nu and then α, the heat transfer coefficient for the improved surface:

$$\alpha_1 = Nu\,\lambda_{gas} / d_к, \qquad (3)$$

where λ_{gas} = 8.27 10-2, W/m deg, is the thermal conductivity coefficient of flue gases at t_{gas} = 700°C. In addition, calculations were carried out using the empirical equation proposed in [12], where the channel height H is taken into account in the geometric coefficient.

$$\frac{Nu}{Nu_0} = 1 + 4{,}4\,[\gamma(h/D)]^{0,8}/(\frac{H}{D})^{0,6}\,, \qquad (4)$$

where H is the channel height, m.

The analysis of (1) and (4) showed that (1) does not take into account the depression diameter D, while (4) does not consider the density of the applied depressions γ. Considering the significance of the parameters D and γ, the authors proposed the following (5) for calculating the heat transfer intensity, which accounts for the influence of both of these parameters.

$$\frac{Nu}{Nu_o} = 1+ (\gamma\,K_{f1})/\,\mathrm{Nuo}, \qquad (5)$$

where $K_{f1} = (\pi(2hr - h^2))/(S_x\,S_z)$,
where r – radius of the depression, m.

3 RESULTS AND DISCUSSION

Numerical calculations for given geometric and thermophysical parameters yielded the following results, some of which are shown in Figure 1, Figure 2, Figure 3, Figure 4, Figure 5, Figure 6.

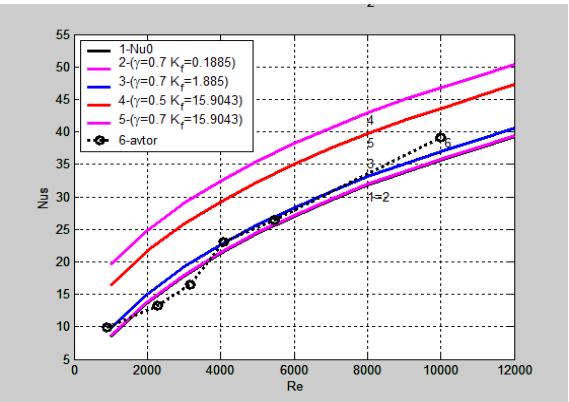


Figure 1: Dependence of the Nusselt number Nu on the Reynolds number Re at various values of γ.

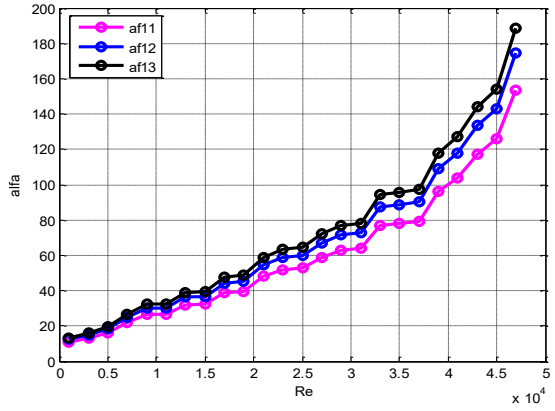


Figure 2: Dependence of the heat transfer coefficient α on the Reynolds number Re for different values of γ.

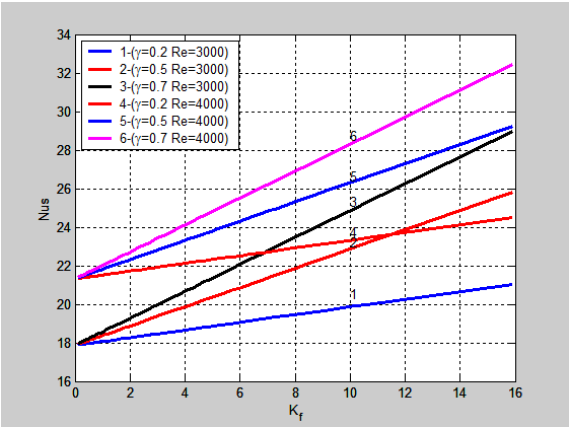


Figure 3: Dependence of the $\frac{Nu}{Nu0}$ ratio on the Reynolds number (Re) for different values of γ and dk.

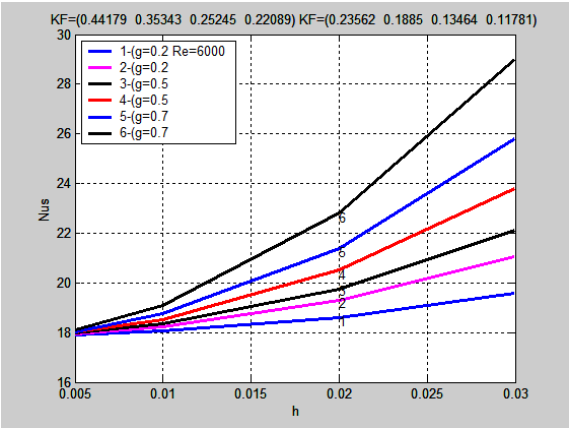


Figure 4: Graph of the dependence of $\frac{Nu}{Nu_0}$ on h, the dimple depth, at different dimple densities γm=0.2; 0.5; 0.7 and at various Kf values (Re= 6000).

Analysis of the obtained calculated curves showed that as the depth of the turbulence-inducing dimples and the area of the surface with such dimples increase, the intensity of heat transfer from the heat carrier to the surface also increases. A similar pattern of the influence of dimple depth on heat transfer intensity at different values of the improved (dimpled) surface area fraction is observed for various Reynolds numbers (Re).

The analysis of the calculated curves presented in Figure 4 shows that an increase in the density of turbulence-inducing dimples (g_m) leads to an increase in heat transfer intensity. Moreover, as the geometric coefficient Kf increases, the enhancement of heat transfer becomes more significant. It should be noted that the nature of the influence of dimple density on heat transfer intensity remains consistent for different Reynolds numbers (Re).

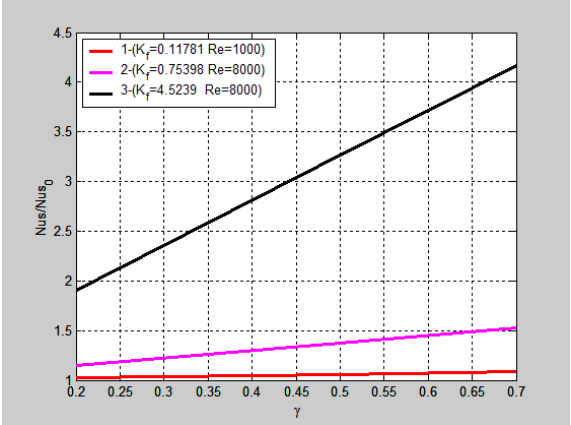


Figure 5: Dependence of $\frac{Nu}{Nu_0}$ on the dimple density γm at different values of Kf=0.11781, 0.7539, 4.5239 (Re= 1000, 8000).

Figure 6 presents graphs of the calculated values showing the influence of the geometric coefficient K_f on the intensity of heat transfer. The analysis showed that as the fraction of the surface improved with turbulence-inducing dimples increases, the heat transfer intensity also increases. An increase in the Reynolds number (Re) likewise leads to an increase in heat transfer intensity.

Special attention should be paid, when designing heat exchange surfaces with turbulizers, to the parameters of dimple arrangement on the surface — that is, to analyzing the influence of the longitudinal and transverse pitches of the dimples, which determine the dimple density coefficient. The influence of the arrangement parameters (transverse and longitudinal pitches) on the heat transfer intensity was investigated numerically (Figures 7 and 8).

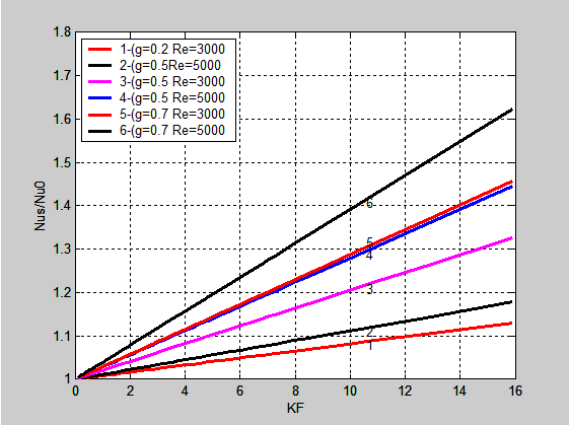


Figure 6: Graph of the dependence of heat transfer intensity $\frac{Nu}{Nu_0}$ on the geometric coefficient Kf at different dimple densities γ = 0.2; 0.5; 0.7 and Re = (3000, 5000).

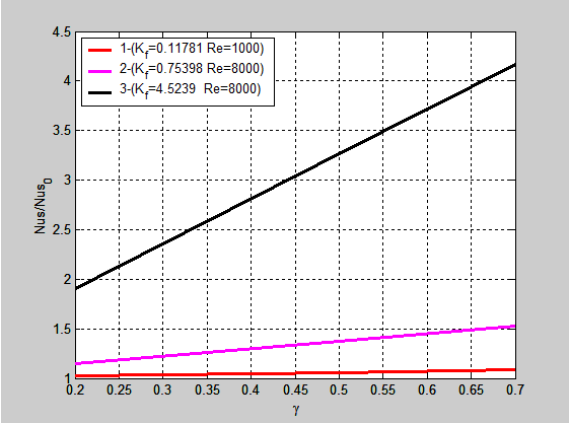


Figure 7: Graph of the dependence of $\frac{Nu}{Nu_0}$ o on Sz at γ = 0.2; 0.5; 0.7 and Re = 6000.

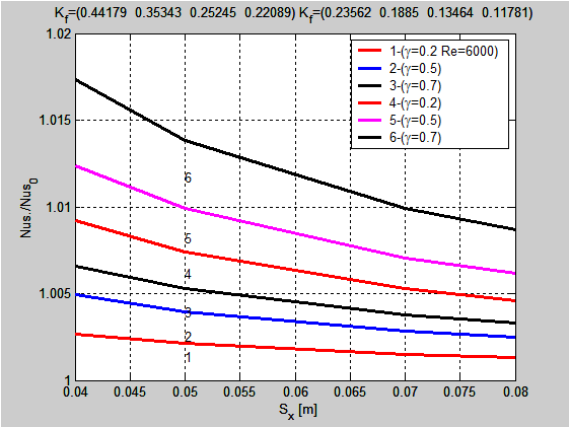


Figure 8: Graph of the dependence of $\frac{Nu}{Nu_0}$ on Sx at γ = 0.2, 0.5, 0.7 (Re = 6000).

The analysis showed that as the geometric parameters of the arrangement of turbulence-inducing depressions increase, the intensity of heat transfer decreases. This is due to the overall reduction of the geometric coefficient Kf and the decrease in the proportion of the enhanced surface.

The authors conducted a comparative analysis of the results obtained using the proposed (5) with the results of studies by other researchers [11], [12]. Figures 9, 10, and 11 present several graphs illustrating this comparative analysis.

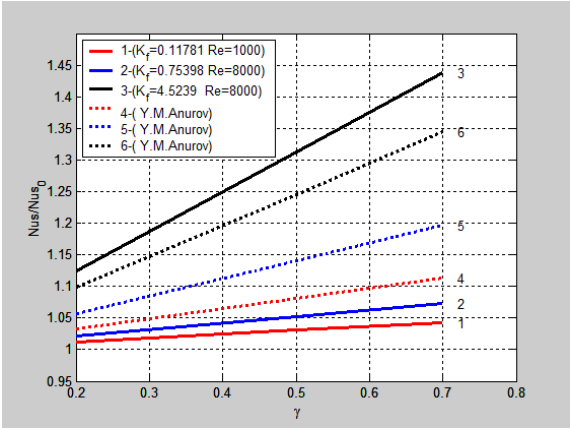


Figure 9: Dependence of the heat transfer intensity $\frac{Nu}{Nu_0}$ on the density of the applied depressions γ.

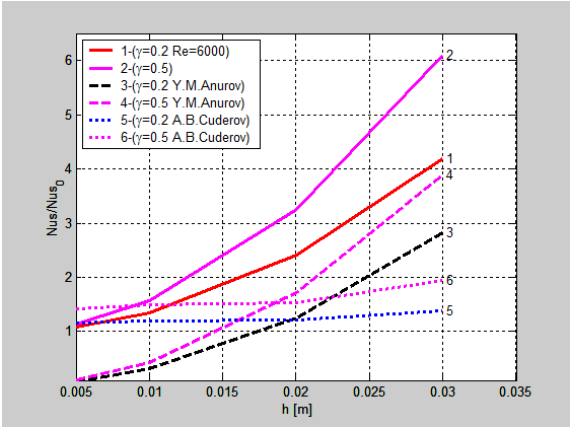


Figure 10: Dependence of the heat transfer intensity $\frac{Nu}{Nu_0}$ on the depth of the turbulence-inducing depressions h.

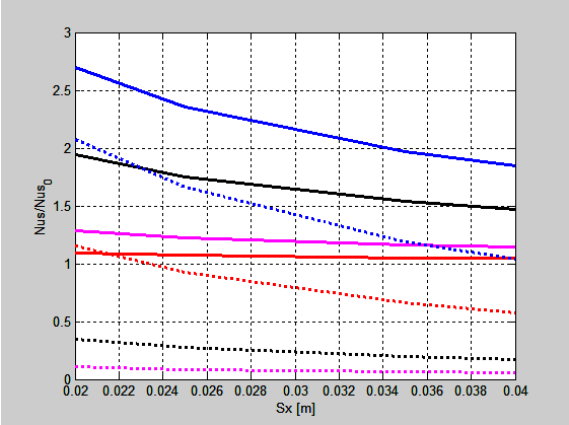


Figure 11: Dependence of the heat transfer intensity $\frac{Nu}{Nu_0}$ on the longitudinal pitch Sx of the depressions arrangement.

4 CONCLUSIONS

The analysis of the obtained dependencies showed that the flow turbulization achieved by applying turbulence-inducing depressions on the heat exchange surface enhances heat transfer. Increasing the depth of the turbulence-inducing depressions (h) together with the density of the applied depressions (γ) contributes to up to a twofold increase in heat transfer, although at certain S_x values, a slight decrease in heat transfer is observed.

An increase in the density of turbulence-inducing depressions at a constant geometric coefficient (K_f) also intensifies heat exchange, though to a lesser extent.

Changes in the geometric dimensions of the depressions likewise affect the heat transfer intensity; with larger dk values, large vortices form in the depression area, leading to a predictable increase in flow turbulence and consequently enhanced heat transfer. Overall, flow turbulization using depressions allows for an increase in heat exchange intensity, which in turn can reduce the initial consumption of organic fuel.

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Performance Enhancement of the Guiding Apparatus in a Nozzle-Type Reaction Micro Hydropower Turbine

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Keywords: Nozzle, Hydroturbine, Internal Flow-Guiding Apparatus, Computational Fluid Dynamics (CFD), Experimental Investigations, Micro-Hydropower Systems, Renewable Energy Technologies.

Abstract: The study addresses the utilization of low-pressure water sources for electricity generation as an important approach to ensuring sustainable energy supply in rural and remote areas. Conventional turbines experience high energy losses, frequent cavitation phenomena, and reduced service life under low-pressure conditions. To overcome these challenges, this research focuses on improving the internal guiding mechanism of a nozzle-type reactive micro-hydroturbine to enhance efficiency, minimize energy losses, and extend operational durability. The main objective is to design and develop a conical confusor-based internal guiding mechanism with optimized blades and to assess its influence on flow stability and efficiency through CFD modeling and experimental verification. The research employs a comprehensive methodology combining analytical analysis, mathematical modeling, and experimental testing. Bernoulli's equations were applied to determine flow velocity and energy losses, while CFD modeling was performed using COMSOL Multiphysics 6.1 software based on the RANS method with a k–ε turbulence model. Flow velocity and pressure distribution were analyzed, and a 500 W prototype of the hydroturbine was experimentally tested under 2–6 meters of water head on a specially designed laboratory stand. The results contribute to improving the performance and operational stability of micro-hydroturbines designed for low-pressure water sources, promoting the wider implementation of sustainable energy technologies in decentralized power systems.

1 INTRODUCTION

According to the International Energy Agency's 2024 report, the reserves of hydrocarbon fuels will historically last for a relatively short time; that is, if consumed at the current rate, natural gas and oil fuels are expected to last for 70–80 years, while coal may last for 150–200 years [1]. In this period of rapidly increasing global energy demand, saving underground fuel reserves and preventing environmental problems require the efficient use of all types of renewable energy sources to produce environmentally clean energy. Therefore, the effective utilization of existing low-head water resources in the field of hydropower, which is one of the renewable energy sources, can also contribute to solving the abovementioned issues. Electricity generation from low-head water resources, especially in rural and decentralized remote areas, can be considered both as a method of organizing power supply based on hydropower systems (rivers, irrigation canals, and small reservoirs) and as an ecological solution through the rational use of water resources. It is well known that when conventional turbines operate under low-head conditions, a number of problems arise. These include strong turbulence, uneven velocity distribution, cavitation, and significant energy losses due to local and hydraulic resistances, resulting in reduced turbine service life. In most hydroturbines, the efficiency does not exceed 70% [2]. Over the past decade, many researchers have worked on improving the performance of hydroturbines designed for low-head operation. This has been done by enhancing the runner wheels and guide vanes, optimizing the nozzle geometry in jet turbines, and improving the design of guide vane geometry [3]. In particular, studies on guide vane

control, turbulence reduction, cavitation mitigation, and overall efficiency improvement have been carried out. Hue L. et al. [4] emphasized that, under low-head conditions, the energy recovery efficiency with guide vanes could be improved by up to 3.11%. Bao Ngoc Tran et al. [5] found that, in guided vane configurations, a combination of eight vanes with a 30° inclination could increase efficiency by 6.3% and power output by 4.2%. Such modeling and CFD analysis results were also reported in the works of Ramalho, R. V. C. et al. [6] and Barsi, D. et al. [7], who showed that regulation of flow could improve hydraulic efficiency across a wide range of operating conditions. Chaulagain, R. K. et al. presented findings on the characteristics of existing turbines. In most cases, research results remain limited to CFD [8]; comprehensive methodologies combining analytical modeling, numerical simulations, and prototype testing have not been sufficiently applied. Furthermore, much of the literature is devoted to medium-scale systems of 20–500 kW, while compact prototypes below 5 kW have not been adequately studied. Yet, such systems are of crucial importance for rural agriculture and electrification of remote networks. Recent studies have analyzed, in detail, the influence of the number and shape of guide vanes as well as additional conical parts on hydraulic losses and overall energy performance using CFD software. For instance, Takamure et al. [9] investigated small hydroturbines with conical devices, determining torque and output power by comparing CFD and experimental results. Their findings confirmed the positive effect of diffusers on the flow process. Shi et al. [10], based on entropy theory, analyzed the effect of different guide vane numbers on energy losses, concluding that an increase in vane number leads to higher efficiency. Yang et al. [11] developed a novel "Split Sliding Guide Vane" (SSGV), which successfully eliminated leakages in the flow and improved system stability. Vijay Kumar et al. [12], by varying the opening degree of guide vanes in a Francis turbine, demonstrated that maximum efficiency depends on the opening angle (≈50.25%). This result provides a methodological basis for determining the turbine's optimal operating regime. Romero-Menko et al. [13] studied cross-flow turbines and showed that the shape and arrangement of internal elements and nozzle configuration significantly affect turbine efficiency. Similar results can be seen in other similar studies on low-head hydroturbines [14]-[17]. The literature review indicates that optimization of internal guide apparatus and CFD modeling contribute significantly to experimental validation. However, the application of conical diffusers and optimized vane geometries in jet hydroturbines has not yet been studied. The novelty of this research lies precisely in this aspect: the combined application of analytical modeling, CFD simulation, and experimental testing to justify the optimal parameters of a jet reaction turbine.

2 MATERIALS AND METHODS

The general scheme of the hydroturbine with an improved internal guiding structure is presented below (Fig. 1).

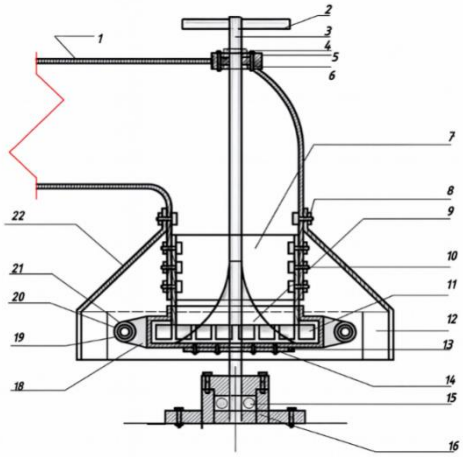


Figure 1: General scheme of the reaction hydroturbine with an improved internal guiding structure: 1 – water inlet channel; 2 – pulley; 3 – shaft; 4 – gland; 5 – bearing; 6 – bearing housing; 7 – supply cylinder of the improved internal guiding structure; 8 – stationary housing of the hydroturbine and fixing bolts; 9 – conical diffuser of the guide device; 10 – attachment bolts of the guide device to the supply pipe; 11 – guide vane profile; 12 – water-returning blades of the stator; 13 – runner cylinder; 14 – cylindrical base connecting the runner to the shaft; 15 – lower base bearing fixed to the dam; 16 – base bearing housing; 17 – platform; 18 – water inlet channel to the nozzle; 19 – nozzle working body; 20 – nozzle diffuser; 21 – water outlet channel and diffuser; 22 – stator of the hydroturbine.

The water flow, maintained at constant pressure in the reservoir, passes through supply pipe (1) into the supply cylinder (7) of the improved internal guiding structure. It then enters the gap between the central conical diffuser (9) and the supply cylinder, which gradually narrows towards the lower section. In this stage, the water flow, initially in the vertical direction, is smoothly redirected into the horizontally oriented guide vanes (11). During this transition, while the flow width remains constant, its direction changes

relative to the radial axis and acts upon the inner wall of the nozzle (18), which is fixed to the runner cylinder (13), at an optimized angle β = 15–18°.

At the nozzle inlet, the flow exerts pressure and active force on the inner surface. After reflecting from the inner wall of the nozzle, the water jet continues toward the diffuser section (20) of the outlet channel (19). The water jet exits the nozzle at high velocity in a compact stream, creating an impulse force in the opposite direction, which generates a reactive force on the nozzle. Consequently, the runner of the hydroturbine rotates in the opposite direction to the water jet. The outgoing jet strikes the vertically positioned stator blades (12) of the stator (22) perpendicularly, after which, under the influence of gravity and the inclination of the stator blades, the water falls downward and exits through the discharge channel. The rotary motion of the runner is transmitted to the generator via the shaft (3) connected to the pulley (2).

The motion of water inside the hydroturbine consists of several stages. Considering the energy loss due to nozzle type, a correction factor φ = 0.95 was introduced. The average velocity of water at the turbine inlet section (υ_1) was calculated using Bernoulli's equations, based on the mean flow velocity up to the entry point of the internal guiding structure vanes [17]:

$$\upsilon_2 = \sqrt{\frac{\frac{\rho Q \upsilon_1}{\gamma S_2}\left(\frac{S_1}{S_2}-1\right)+\frac{\alpha_1 \upsilon_1^2}{2g}-\sum h_{1i}+z_1-z_2}{\alpha_2}\cdot 2g}, \quad (1)$$

where F_d – cross-sectional area of water flow at the turbine inlet (minimum section); F – cross-sectional area of the supply pipe; υ_1 – average velocity at turbine inlet; Q – flow rate.

To analyze the motion of water through the internal guiding structure, the schematic diagram shown in Figure 2 was used.

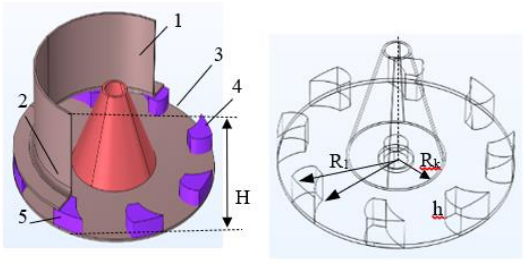


Figure 2: General schematic view of the improved internal guiding structure: 1 – supply cylinder; 2 – annular upper disc; 3 – lower disc; 4 – guide vanes; 5 – water outlet from the guiding structure.

Let υ_2 denote the average velocity of water exiting through the channels between discs (2) and (3). When the water is redirected from vertical to horizontal channels, energy losses occur due to the 90° turn and friction with the guide vanes. However, since vane dimensions are relatively small, frictional losses can be neglected. To ensure no energy loss when water flows from the supply cylinder to the nozzle, the cross-sectional area of the supply cylinder (S_2, with diameter d_2) must equal the total inlet area of the channels. The channels are placed symmetrically along the cylinder periphery. Assuming all dimensions are identical, the vane height H_k is determined by:

$$H_k = \frac{\pi d_2}{2k\varphi\alpha}, \quad (2)$$

$$\varphi = \frac{\alpha d_2 - \delta}{\alpha d_2}, \quad (3)$$

where k – number of vanes; φ – flow coefficient at vane entrance; α – central angle between adjacent vanes; δ – sum of vane thickness and blocked arc length for fixing.

Based on Zhukovsky's theory, the velocity of water exiting the guiding structure is given by:

$$\upsilon_3 = \upsilon_2\left(\frac{kl\sin\alpha_1}{d_2}+\cos(\alpha_2-\alpha_1)\right) \quad (4)$$

where l – vane length; α1, α2 – entry and exit angles of the guide vanes.

The total energy loss of the water flow in the turbine is determined as:

$$h_G = \left(\frac{S_1}{S_2}-1\right)^2\frac{\upsilon_1^2}{2g}+\xi_{90^\circ}(1-\cos\varphi_2)\frac{\upsilon_3^2}{2g}+\xi_{SK}\frac{\upsilon_3^2}{2g}+\left(\frac{S_3}{S_6}-1\right)^2\frac{\upsilon_4^2}{2g} \quad (5)$$

where ξ – hydraulic resistance coefficient; α – cone formation angle; ψ – proportionality coefficient (ψ = 2 for pipes, ψ = 1 for rectangular sections); λ – Darcy friction coefficient.

The torque and angular velocity of the runner were determined using the general theorem on the variation of angular momentum for a rigid body:

$$\omega_z = \frac{S_3\upsilon_3^2\left(\cos\beta+\sqrt{\frac{S_3}{S_6}\left(\frac{S_3}{S_6}-1\right)+1-\frac{1}{2}\left(\xi_{SK}+\xi_{90}\right)}\right)}{\pi r_c^3\upsilon_4}+\frac{\upsilon_4}{r_c}; \quad (6)$$

where r_c – distance from the rotation axis to nozzle center; υ_3, υ_4 – water velocities at nozzle inlet and outlet.

Table 1: Parameters introduced in mathematical modeling.

Name	Expression	Value	Description
dens	1000[kg/m^3]	1000 kg/m³	Water density
visc	8.9e-4[Pa*s]	1E−5 Pa·s	Dynamic viscosity of water
vs	6[m/s]	6 m/s	Water inlet velocity into the nozzle
Re	2*R1*vs*dens/visc		Reynolds number
Q	0,2[m^3/s]	0,2 m³/s	Water flow rate
H	2,5 [m]	2,5 m	Static head of water
omega z	6,6 [rad/s]	6,6 rad/s	Angular velocity of the runner
bm	0,004[m]	0,004 m	Thickness of the nozzle wall
alfa1	15[grad]	0,2618 rad	Water inlet angle to runner guide vane
alfa2	12[grad]	0,20944 rad	Water outlet angle from runner guide vane
betta	15[grad]	0,2618 rad	Installation angle of the guide vane relative to radial direction
lamb	0,05	0,05	Darcy friction coefficient
G	9,81[m/s^2]	9,81 m/s²	Gravitational acceleration
N	8	8	Number of guide vanes
fi_0	0,95	0,95	Water inlet coefficient
hi	15[grad]	0,2618 rad	Diffuser angle at nozzle outlet
R_1	(Q/(3,14*fi0*(2*g*H)^0,5))^0,5	0,10346 m	Inlet pipe radius to hydroturbine
R_2	0,98*R1	0,10139 m	Radius of supply cylinder in guiding device
myu	S3/S4	3	Ratio of inlet to outlet areas of nozzle
delta	0,02[m]	0,02 m	Distance between runner cylinder and guide vane
Hk	0,026[m]	0,026 m	Radial height of the guide vane
m	4	4	Number of nozzles
Rs	Hk + delta + bm + R2	0,15139 m	Distance from runner center to nozzle
p	10	10	Percentage of circle occupied by nozzle fixing
alfa	2*pi/m*n[deg]	0,21932 rad	Nozzle occupied angle
v_2	(fi0/R2^2)*(2*g*H*(R1^4 - R1^2*R2^2 + R2^4))^0,5	6,0774 m/s	Velocity of water at guide vane inlet
Lk	R2/myu	0,033796 m	Guide vane length
v_3	(Lk*m*v2*sin(alfa1)*cos(alfa2 - betta))/(2*R2) + v2*cos(alfa2 - alfa1)	7,1162 m/s	Velocity of water at nozzle inlet
L	Q/((1 - p/100)*Rs*v3*2*3,14/m)	0,13139 m	Vertical height of nozzle
S_3	2*3.14*Rs*(1 - p/100)*L/m	0,028105 m²	Nozzle inlet area
S_4	S3/2,5	0,011242 m²	Nozzle outlet area
eps_k	0.125*lamb*(1 - (S4/S3)^2)	0,00525	Energy loss coefficient in nozzle
sig	(d*(d - 1) + 1 - (eps_k + 1.25)/2)^0.5	2.0304	Intermediate calculation coefficient
v_4	v3*sig	14,449 m/s	Velocity of water at nozzle outlet
c	S3*v3^2*(sin(betta + sig))/(3.14*v4)	0,023557 m³/s	Defined coefficient
Rshould d	1.7*Rs	0,25736 m	Arm of force

The energy parameters of the hydroturbine were analyzed using mathematical modeling. CFD simulations were carried out in COMSOL Multiphysics 6.1 (CFD module), applying the standard RANS method and the "Turbulent Flow, k-ε" model for five different guide vane and cone geometries. The velocity and pressure variations of water at different points of the nozzle were studied through mathematical modeling depending on nozzle geometry and number. This model achieves high accuracy in calculating Reynolds shear stresses and tensors for low-head flow gradients.

The dimensions and parameters of the small experimental hydroturbine used for simulation and laboratory testing are presented in Table 1.

3 RESULTS AND DISCUSSIONS

Figures 3 and 4 illustrate the changes in velocity and pressure fields of the hydraulic reaction turbine for both the conventional (non-improved prototype) and the improved internal guiding structures.

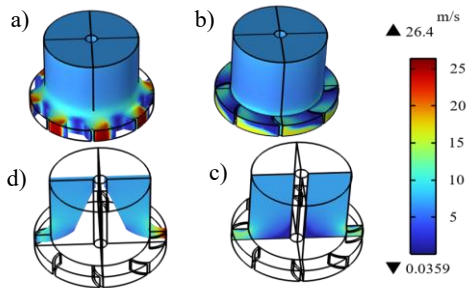


Figure 3: Analysis of water flow velocity field in hydroturbine guide devices: (a) 3D view of water flow in the improved guiding device; (b) 3D view of water flow in the conventional device; (c) water flow characteristics in the XOZ plane of the improved guiding device; (d) water flow characteristics in the XOZ plane of the conventional guing iddevice.

As can be seen from Figure 3, in the conventional turbine (right), multiple red and yellow zones (~20–26) are present around the device. These zones indicate strong turbulence, vortices, or regions of flow acceleration and deceleration. Particularly between the lower vanes, strong flow irregularities and energy losses are observed. In the improved turbine (left), the color gradient is smoother, dominated by blue and green areas (~5–15), which reflects a more stable flow - laminar or optimally turbulent. The flow is more centralized with fewer vortices and reduced turbulence.

Focusing on the inter-vane flow, in the conventional turbine, high-velocity regions in the lower section change abruptly, producing swirling motions inside the flow that generate additional resistance and reduce efficiency. In contrast, in the improved turbine, the inter-vane flow is more centralized and smoother. This condition indicates reduced energy losses and better conversion of flow energy into mechanical energy, attributed to minimized heat losses and vortex formation in the improved design.

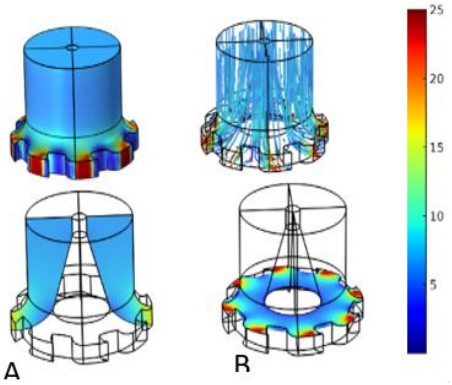


Figure 4: Fluid interaction in the improved internal guiding device of the hydroturbine: (A) velocity distribution; (B) pressure distribution.

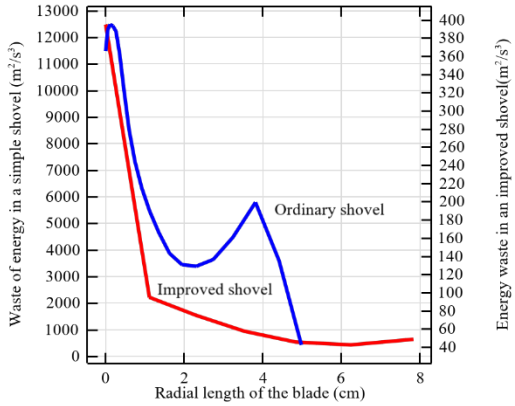


Figure 5: Energy losses due to turbulence in conventional and improved guiding devices with vanes.

From the pressure distribution analysis shown in Figure 4, it is evident that in the conventional guiding device, the water jet exiting the window expands and produces a vortex-like motion, leading to significant energy dissipation due to eddies and sudden expansion. This reduces the torque applied to the runner. In contrast, in the improved guiding device, the water flow passes through the guiding window without changing the spacing between the vanes,

directed toward the nozzle walls, producing maximum torque on the runner. The properly aligned and accelerated jet towards the nozzle walls increases turbine efficiency.

As illustrated in Figure 5, comparison of the flow zones between conventional and improved vane-type hydroturbines reveals the following observations:

- In the initial zone (0 – 1.5 cm), the turbulence dissipation rate is very high (~5000+ m^2/s^3) for the conventional vane design (blue), whereas in the improved vane design (red/green), turbulence and energy dissipation are significantly lower. The smoother acceleration of the flow in the improved vane reduces energy losses.
- In the middle zone (1.5 – 6 cm), turbulence sharply decreases (from 5000 → ~1000 m^2/s^3), indicating rapid attenuation of instability in the flow. The improved vane maintains flow stability over a longer distance, which enhances aerodynamic efficiency and reduces system friction.
- In the final zone (6 – 13 cm), the velocity in the conventional vane device drops considerably (~9 m/s), while in the improved vane device, velocity remains higher (~10–11 m/s). This demonstrates that energy is dissipated more slowly.

Thus, in the improved vane design, the flow remains more stable and energy-rich, ensuring improved heat transfer and higher driving power. Due to reduced turbulence and sustained high velocity, cavitation decreases, and the service life of the turbine is nearly doubled.

A small-scale model of the hydroturbine was fabricated and tested experimentally. The experimental results were compared with those of the conventional prototype.

It was found that there are almost no dedicated stands available for testing small-scale hydroturbine models; existing stands are large in size, equipped with outdated components, and suitable for testing only one or two turbine types with limited capability to vary water head and flow rate. Moreover, constructing a new turbine prototype for such stands requires significant financial costs.

Therefore, a test stand was developed that allows experimental studies of various pico-hydroturbine prototypes, along with a testing methodology (Fig. 6).

The fabricated stand has the following structure: a frame with two reaction hydroturbines installed, supplied with water through three low-pressure pumps (1.5 kW each). The inlet water pressure of the hydroturbine is monitored using four manometers. The rotary motion from the turbine shaft is transmitted via a pulley to a generator, with a transmission ratio of 2.2. The generated electricity is supplied to a specially designed transformer. The transformer output, including current and voltage, is measured and displayed on a control panel. As a load, two 50 W lamps and a 150 W resistance coil were used. The generated current and voltage were measured using Class A ammeters and voltmeters.



Figure 6: Experimental setup of the improved micro-hydroturbine model.

The water flow rate and pressure were regulated by controlling the rotational speed of the pumps using a frequency regulator, with the range varying from 0 to 5000 rpm. Additionally, water circulation before the pump was provided through valves to extend the range of flow and pressure control.

The small-scale nozzle-type reaction hydroturbine model was tested on this stand. During the experiments, water pressure at different points in the turbine was measured using manometers, the water flow rate was determined from a calibrated scale in the measuring tank, and the runner's rotational speed was measured using a tachometer.

The analytical, numerical, and experimental investigations conducted in this study demonstrate that the proposed internal guiding device - consisting of a diffuser cone and optimized guide vane geometry - significantly improves the performance of nozzle-type reaction turbines under low-head conditions.

Compared with the conventional design, the efficiency of the improved turbine reached 85.5%, which is 3.4% higher than that of the conventional turbine (82.1%). This increase in efficiency primarily results from two mechanisms: (i) the conical diffuser stabilizes the inlet flow to the guide vanes, reducing turbulence and secondary vortices; and (ii) the optimized guide vane geometry minimizes hydraulic losses and enhances energy transfer to the shaft.

In addition, the maximum rotational speed increased by almost 14%, confirming the enhancement of energy efficiency.

A comparison of analytical, CFD, and experimental results further supports these findings. Analytical evaluation showed an efficiency of 86.2%, CFD simulations yielded 86.6%, and experimental measurements recorded 85.5%. The close agreement between these values demonstrates the reliability of the proposed design and the validity of the adopted methodology. A deviation of less than 1.5% confirms that CFD, when supported by analytical theory and validated through experiments, can serve as an effective predictive tool for turbine optimization.

From a practical standpoint, the improved turbine is particularly well suited for rural electrification and irrigation canal systems, which are widely implemented in Uzbekistan and other developing countries. By reducing the risk of cavitation and extending the service life of the turbine by approximately 50–55%, the design not only enhances efficiency but also decreases maintenance costs and downtime, thereby improving overall economic feasibility.

4 CONCLUSIONS

This study focused on the improvement of the internal guiding device of a nozzle-type reaction turbine under low-head conditions through CFD modeling and experimental testing. The novelty of the work lies in the use of a conical diffuser and optimized guide vane geometry to control flow, reduce hydraulic energy losses, and enhance both efficiency and turbine service life.

The research employed analytical evaluation of flow, velocity, torque, and efficiency; CFD simulations using the RANS approach with the k–ε turbulence model in the COMSOL Multiphysics platform; and experimental testing of a 500 W prototype on a specially designed laboratory stand with an adjustable water head of 1.5–6 meters.

The results provided new scientific insights into the influence of internal guiding devices on turbine performance. The improved design reduced hydraulic losses by 35–40%, increased efficiency from 82.1% to 85.5%, and extended turbine service life by approximately 50–55%.

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Using Hybrid Energy Storage System for Grid-Connected Photovoltaic Applications

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Keywords: Modelling, Supercapacitors, The Maximum Power Point Tracking MPPT, Bidirectional DC-DC Converters (BDC) Buck/Boost, PI Controller, Energy Density, Power Density.

Abstract: This paper presents the design and modeling of a hybrid energy storage system (HESS) for a grid-connected photovoltaic (PV) application. The proposed system integrates batteries and supercapacitors to address the inherent variability of solar power generation and to enhance grid stability. A boost converter is employed to regulate and elevate the PV output voltage, while a maximum power point tracking (MPPT) algorithm based on the incremental conductance method ensures optimal energy extraction under varying environmental conditions. The system is interfaced with the grid through a three-phase voltage source inverter controlled by pulse width modulation (PWM). The hybrid storage configuration combines the high energy density of batteries with the high power density of supercapacitors, enabling efficient management of both low-frequency and transient power fluctuations. A bidirectional DC–DC buck–boost converter with PI-based control is used to coordinate charging and discharging processes. Simulation results demonstrate that the proposed system effectively reduces power fluctuations, minimizes grid dependency during peak demand, and improves overall system reliability. Furthermore, the hybrid approach alleviates battery stress, thereby extending its operational lifetime. The study confirms that integrating hybrid energy storage significantly enhances the performance and stability of grid-connected PV systems.

1 INTRODUCTION

The power generation from renewable energy sources is inherently variable due to their dependence on fluctuating weather conditions. For instance, the energy output from recently deployed photovoltaic systems is highly variable [1], [2]. These energy fluctuations pose challenges to the stability of the public grid and the overall power system. Therefore, the use of energy storage systems can mitigate these instability issues. Since the inception of electrical energy generation, various effective technologies have been developed to store and utilize energy when demand arises. The energy storage industry has continued to evolve and advance technically, diversifying both the technologies and the methods for controlling power sources. This diversification aims to create a flexible energy infrastructure and achieve cost savings for both network owners and consumers. Batteries have been utilized as a crucial storage element, with research identifying the optimal size to minimize total operating costs [1]. Additionally, other energy storage systems, such as supercapacitors, have been employed to address the variability in the output power of distributed photovoltaic systems injected into the grid, demonstrating their impact on the safety and reliability of distribution networks [2]. Figure 1 illustrates the energy density and power density of each storage type, thereby determining the optimal operating range for each.

The concept of power density, which represents the maximum power that can be extracted per unit mass (W/kg), and the concept of energy density, which denotes the energy that can be expended from the source per unit mass (Wh/kg), are pivotal in the realm of energy storage. These concepts determine the optimal energy source based on the application. For instance, for long-term operation, sources with high energy density, such as certain storage

technologies with high energy density, are preferred to extend the operating time of the load. Conversely, when a large capacity is required irrespective of time, supercapacitors with high power density (KW/kg) are more suitable, making them ideal for applications like engine starting or braking [3], [13]. Consequently, it has been found that the advantages of both storage elements can be harnessed through a hybrid storage system. This system comprises as Figure 2.

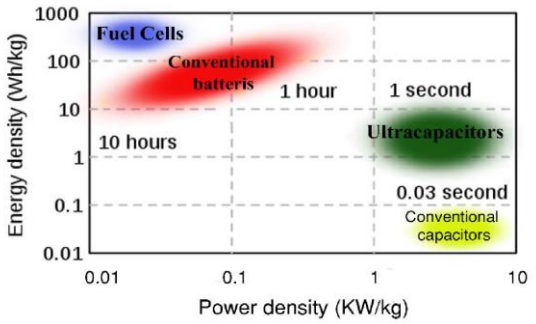


Figure 1: Energy density and power density of supercapacitors and Batteries [3], [13].

Energy Storage unit (ESU1): Designed to meet high power demand and rapid, transient load changes, characterized by fast response time, high efficiency, and long-life cycle.

Energy Storage unit (ESU2): Intended for high energy storage, characterized by a low self-discharge rate and low energy installation cost [4], [14], [28].

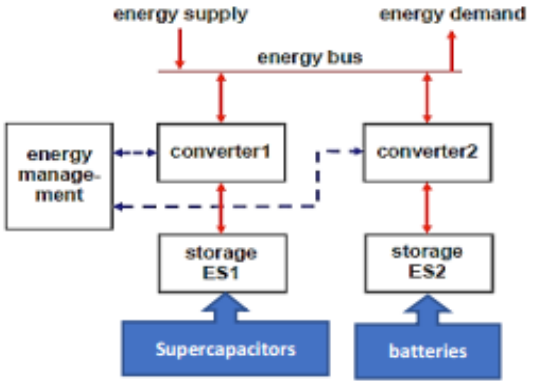


Figure 2: Basic structure of hybrid storage system.

The two storage units are charged and discharged using a bidirectional DC/DC converter. Borkowski ,D. Oramus ,P & Brzezinka ,M In [1], a dedicated control strategy for PV-BESS that maximizes the daily market DM revenue is proposed. The algorithm for determining the control strategy was implemented using analytical methods based on complete data on PV production and energy prices. Furthermore, the control strategy was implemented in a sizing algorithm that optimized the financial criteria. The effectiveness of the algorithm was demonstrated through an example of real 1 MW PV data. A 10-year analysis of the system operation using the additional control mode indicated a significant increase in the rate of return of the energy storage, reaching 15 % for the high PV penetration price profile. Gonçalves, A. Cavalcanti, G & Feitosa, M&..etc In [2] the size of the BESS system was determined to supply energy to the load of auxiliary systems of an ESS, as well as a PV system to achieve a null total cost. Furthermore, multi-objective optimization using the genetic algorithm technique was employed to optimize the size of the hybrid PV/BESS to minimize the investment cost and time when the demand was not met. Simulations under different scenarios of contingency were allowed to obtain the Pareto frontier for the optimal sizing of a PV/BESS system to supply energy to AC auxiliary systems in an ESS under contingency. Member, S., & Ongaro, F [3].at the University of Udine, Italy, this study focused on extending the lifespan of batteries powering wireless sensors. A DC-DC converter was used to control input voltage and increase power, while a statistical method based on recorded energy data determined the energy storage elements' size. Results showed a significant reduction in charge/discharge cycles of Li-ion batteries, improving their lifespan and confirming the design procedure's validity. Karshenas, Kurtoğlu1, M,&Eroğl, F. In [4] a non-isolated BDC, has a buck and boost principle of operation, is designed, analysed and simulated under various case studies. In the designed system, BDC controls the bidirectional power flow between the battery and DC link. Specifically, in the charging stage of battery operating in buck mode, DC-link supplies the power to the battery and BDC regulates the battery current using proportional-integral (PI) controller. On the other hand, in the discharging stage of the battery operating in boost mode, when DC source is disconnected, the battery supplies the power to DC load and DC-link voltage is controlled by the BDC via PI controller. The simulation results are presented to show the operation and control of the BDC under different scenarios. Manuel, V., & Guerrero, M.Á [5] This research presented a 30 KW photovoltaic system connected to the grid, aiming to develop a method for calculating energy storage system size using energy curves and fuzzy control methods. As for Rajasekaran, R., & Rani, P.U [6] this study employed an energy management algorithm for a standalone

(PV + wind) system to achieve microgrid self-sufficiency. In [7] discusses the transition to renewable energy systems and the challenges of energy storage within them. It addresses the issues of optimizing the capacity of hybrid energy storage systems and their environmental impact. The study presents new strategies to enhance the utilization of these systems and reduce greenhouse gas emissions. Saritha.K.& Sharma.S & another [8] discusses green energy storage technologies, which are a key element in reducing carbon emissions and integrating renewable energy sources. It examines the use of Energy Storage Systems (ESS) to store surplus electricity and make it available on demand to reduce fluctuations. The study reviews green energy storage systems and presents new strategies to enhance their utilization and reduce greenhouse gas emissions.

The current work aims to design and model a hybrid storage system of batteries and supercapacitors for a photovoltaic system that can be connected to the grid. This system can connect regardless of source voltage changes and works to elevate and regulate the output voltage of the photovoltaic system using a boost converter, to operate at the maximum power point of the cells' output. The output voltage then feeds a three-phase voltage inverter driven by PWM (Pulse Width Modulation) technology. When the output power of the photovoltaic system decreases, the stored energy in the batteries and supercapacitors can be utilized, as illustrated in Figure 3.

Based on this study, a hybrid storage system comprising batteries and supercapacitors, along with the necessary bidirectional DC/DC converter (buck-boost) for charging and discharging, was adopted in this research.

2 SYSTEM CONSTRUCTION

The subsequent sections will outline the design equations necessary for a grid-connected photovoltaic system is depicted in Figure 4 (PV system, Boost Converter, Three-phase inverter, Passive filters and grid). as well as the equations required for designing the hybrid storage system and its control components. Additionally, the computer model used to evaluate the overall system performance will be presented.

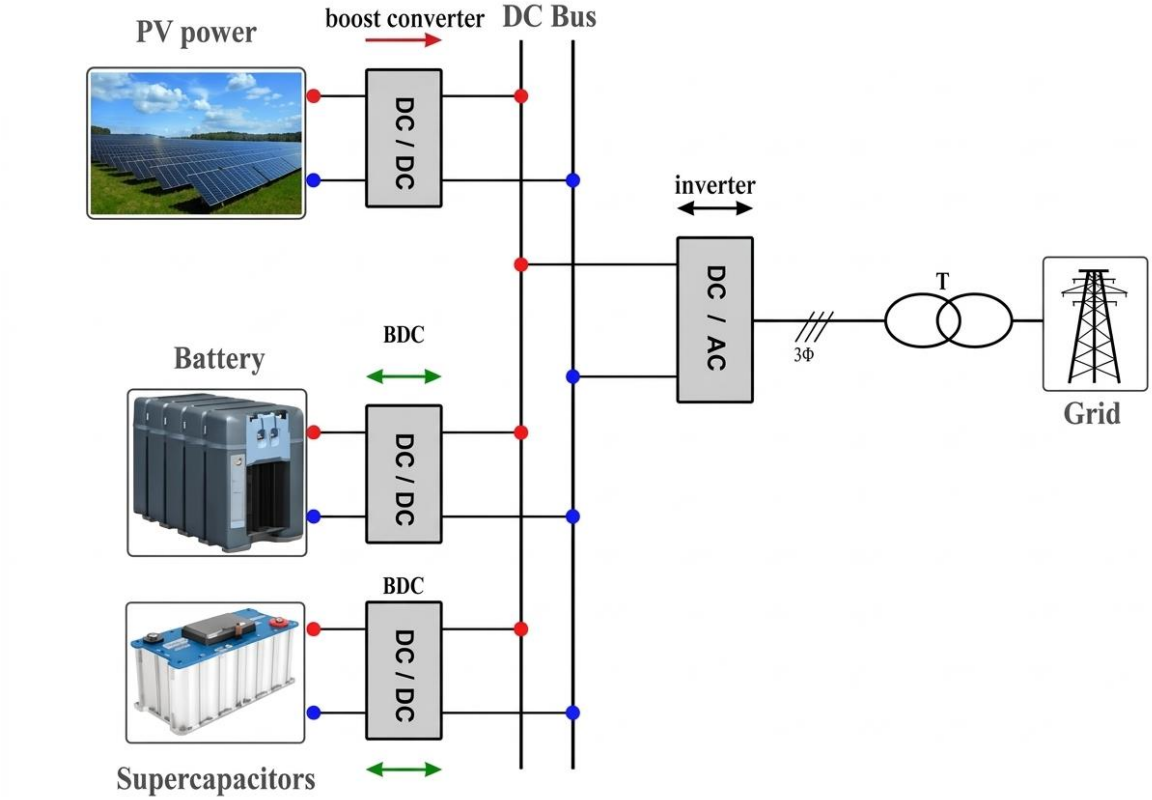


Figure 3: Basic components of the system [9].

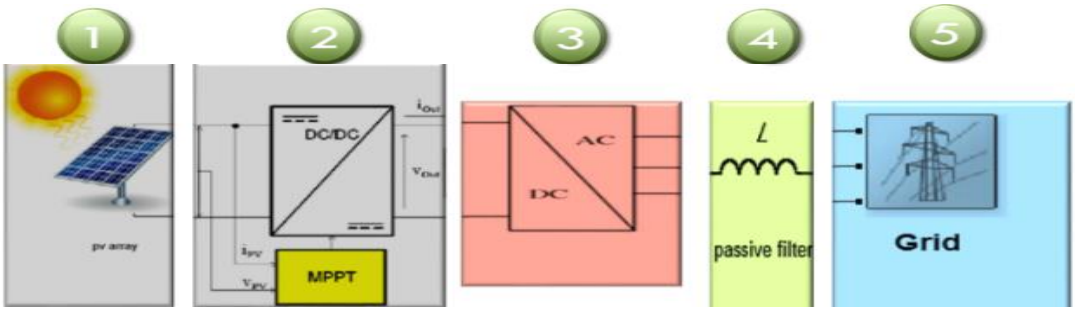


Figure 4: Steps for designing and modeling a grid-connected photovoltaic system.

2.1 PV System

The photovoltaic system array consists of multiple strings connected in parallel, where the total number of modules is calculated using the following relationship:

$$N_{modul} = \frac{P}{P_m}. \quad (1)$$

- P: PV system power [W], P_m: PV module power [W].

The number of modules in a string is calculated as follow

$$N_{m,string} = \frac{V}{V_m}. \quad (2)$$

- V: PV system voltage [V], V_m: PV module voltage [V]

The number of strings connected in parallel is given by:

$$S_p = \frac{N_modul}{N_(m,string)}. \quad (3)$$

To design a photovoltaic array with a capacity of 10 [kW] and maximum output voltage of 200 [V] and select a module with a capacity of 630 [W] and maximum output voltage of 46.02[V], the components of the array are determined based on the relationships above (1), (2) and (3):

$$N_{modul} = 16\ ,\ N_{m,string} = 4\ ,\ S_p = 4.$$

2.2 Boost Converter

The boost converter functions to elevate the output voltage of the PV array, as illustrated in Figure 5.

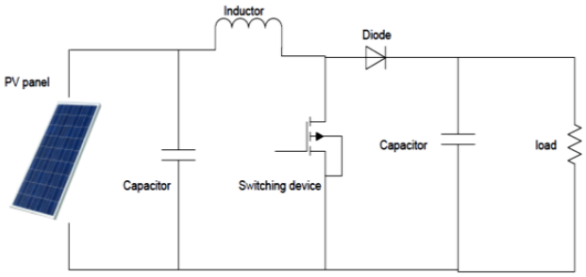


Figure 5: Components of the Boost Converter [10].

The duty factor D, inductor L and capacitor C of converter is calculated according to [15]:

$$D = 1 - \frac{V_i}{V_o},\ L = \frac{(1-D)^2 \times D \times R}{2F},\ C = \frac{D \times V_o}{R \times F \times \Delta V_O}. \quad (4)$$

- V_I: converter input voltage [V];
- V_o: converter output voltage [V];
- R: output resistance [Ω];
- F: chopping frequency [HZ];
- ΔV_O: output voltage ripple [%].

In order to design a boost converter, its input voltage is equal to the output voltage photovoltaic array, 200[V], and its output voltage is 400[V] with ΔV_O<1%, R =500 [Ω], F =50000[HZ] assumed.

Using (4) the nominal values of the elements are determined:

D= 0.5, L= 625*10-6 [H], C = 888*10-6 [F]

2.3 Maximum Power Point Tracking (MPPT)

The incremental conductance method has been selected due to its effectiveness in handling significant variations in weather conditions [16]. This method depends on the values of the slope of the (P-V) curve as in Figure 6.

At the maximum power point:

$$\frac{dI_{PV}}{dV_{PV}} = -\frac{I_{PV}}{V_{PV}}.$$

To the left of the maximum power point:

$$\frac{dI_{PV}}{dV_{PV}} > -\frac{I_{PV}}{V_{PV}}.$$

To the right of the maximum power point:

$$\frac{dI_{PV}}{dV_{PV}} < -\frac{I_{PV}}{V_{PV}}.$$

Therefore, the flow chart for this method is as shown in Figure 7. Figure 8 shows modeling of this method in Matlab.

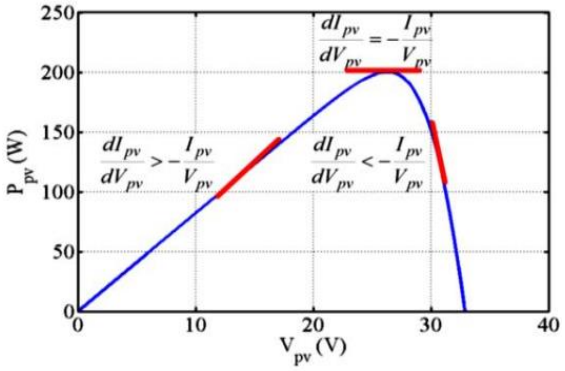


Figure 6: Illustrates the method of increasing conductivity by inclining (power-voltage) curve [10], [16].

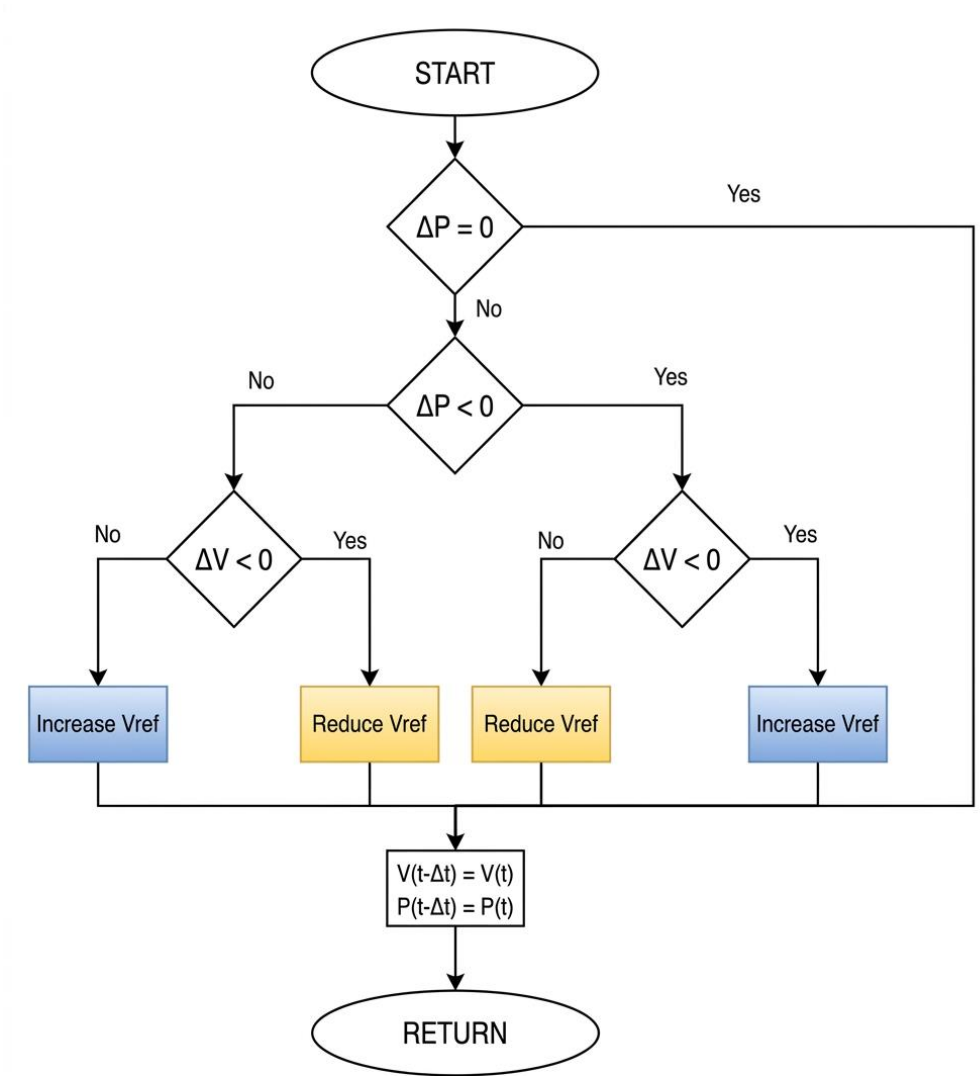


Figure 7: Flow chart of the conductivity increase method [10].

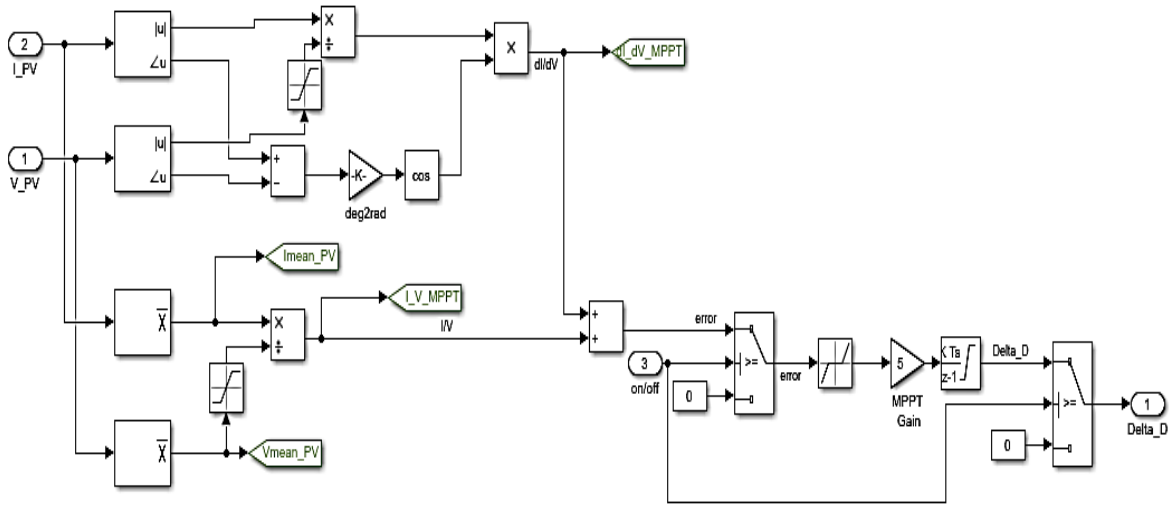


Figure 8: Modeling the conductivity increase method in Matlab.

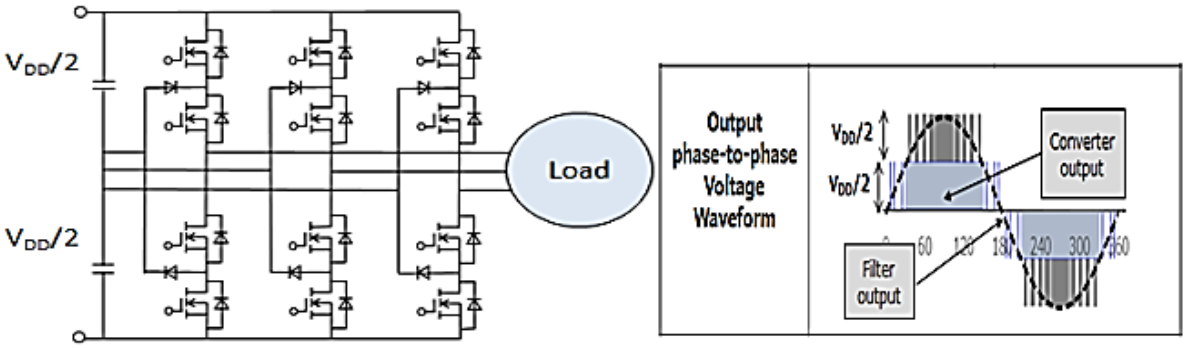


Figure 9: Three-phase inverter structure.

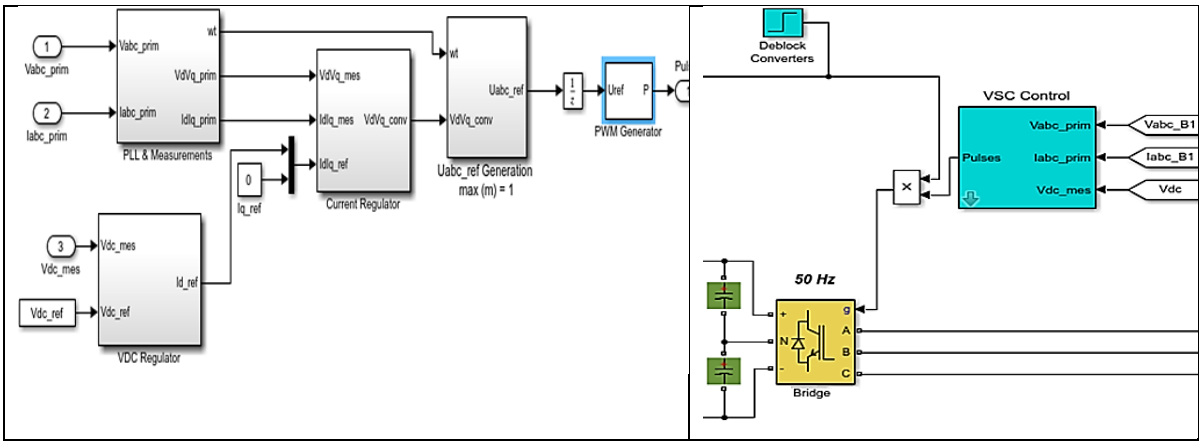


Figure 10: Modeling of a three-phase inverter driven by PWM technology.

2.4 Three-Phase Inverter

The DC input voltage of the inverter must be:

$$VDC > [\sqrt{2}\ V_g\ ]. \quad (5)$$

V_g: grid voltage.

$$VDC > (\sqrt{2} \times 220) > 311 = 400\ [V]$$

The three-phase three-level bridge as shown in Figure 9 is a bridge consisting of three arms, each arm having four IGBT elements, two upper and two lowers [17]:

The three-phase inverter-driven PWM is modeled as shown in Figure 10.

2.5 Passive Filters

A three-phase transmission line, which functions as an inductor, is utilized to transfer the maximum power from the photovoltaic panels to the public grid [18]. The inductance is calculated using following:

$$L = \frac{E^2}{2\pi F \times P_{max}}. \quad (6)$$

E: line voltage of grid [KV]. P max: maximum power transmitted by three phases [MW]. F: grid frequency [HZ].

Considering: P_{max} =10[KW] = 0.01[MW]، F =50[HZ]، E= 380[V] =0.38[KV].

The value of inductance for each phase is:

$$L = 0.38^2 / (2\pi \times 50 \times 0.01) = 0.046[H] = 46[mH]$$

This inductor also acts as a passive filter for current, then photovoltaic system is connected to a transformer center that raises the voltage from 380[V] to 20[KV] and then to public grid 20[KV].

3 HYBRID ENERGY STORAGE SYSTEM (HESS)

The maximum energy required to be provided by the hybrid storage system must be known, as calculated from [5], [19]:

$$E_{max} = \frac{P_{PV,nom}}{3600 \times T_m}. \quad (7)$$

- $P_{PV,nom}$: Nominal power generated by the cells [KW];
- T_m: Power management time [S].

Assuming that: $P_{PV,nom}$= 10 [KW], Tm=30[min]×60=1800[S]

We find: E max="10[KW]" /3600×1800 [S]=5 [KWh].

The percentage distribution of energy between batteries (E_b) and supercapacitors (E_{sc}) is calculated based on the ratio between the time constant of the battery response (τ), which is inversely proportional to the battery stress, and the energy management time Tm, batteries and supercapacitors energy is given as follows [11]:

$$E_b = \frac{1-\tau}{T_m} \times E_{max}, E_{sc} = \frac{\tau}{T_m} \times E_{max}, \quad (8)$$

We will design a hybrid storage system (comprising batteries and supercapacitors) following these steps:

1) Determine the parameters of the batteries (number, type, and specifications).
2) Determine the parameters of the supercapacitors (number and specifications).
3) Design a Buck/Boost converter for charging and discharging the batteries and supercapacitors

3.1 Battery Parameters

Lithium-ion batteries were selected due to their numerous advantages over other types, including higher efficiency and energy density (90%, 125 [Wh/kg]), increased nominal voltage (3.7 [V] per cell), lower weight, longer lifespan, faster and more efficient charging, smaller size, no maintenance requirements, and greater resistance to external conditions [11], [20].

Therefore, we select a GTK Lithium-ion battery C-2440H, with the following specifications [21]:

U_b = 24 [V], Cb = 30 [Ah] : τ=2.4 [min]

And considering: T_m = 30[min], and by compensating for (8) is:

$$E_b = 4.6\ [KWh]$$

To determine the number of batteries needed, we follow these steps:

1) Determine the required voltage of the battery matrix:

$$U_{b-total} = 200\ [V].$$

2) Determine the amount of energy required from the batteries:

$$E_b = 4.6/0.7 \approx 6\ [KWh].$$

Note: Since lithium-ion batteries operate in the capacity range of 25-95%, for safe use, only 70% of the theoretical energy is available [10][22]. Therefore, the calculated value of the total energy that

the battery should provide should be divided by 0.7 to obtain the correct values.

3) Calculate the total capacity of the batteries:

$$C_b = \frac{E_b}{U_{b-total}} = 30\ [\text{Ah}]. \quad (9)$$

4) Calculate the number of batteries in series:

$$N_S = \frac{U_{b-total}}{U_b} = 200/24 \approx 8. \quad (10)$$

5) Calculate the number of parallel strings:

$$N_B = \frac{C_{b-total}}{C_b} = \frac{30}{30} = 1. \quad (11)$$

6) Calculate the total number of batteries:

$$N = N_s \times N_b = 8. \quad (12)$$

3.2 Supercapacitors Parameters

From (8) in the previous section, we determined that the energy required from supercapacitors is:

$$E_{sc} = \frac{\tau}{T_m} \times E_{max} = 0.4\ [\text{kWh}].$$

To determine the specifications and number of capacitors, we select a supercapacitor from Maxwell Company, model BMOD0165 P048 C01with the following specifications [23]: U_{sc}=48 [V], C_{sc}=165 [F].

To determine the number of supercapacitors required, we follow these steps:

1) Determine the required capacitor array voltage:

$$U_{sc-total} = 200\ [\text{V}]$$

2) Determine the amount of energy required from the supercapacitor:

$$E_{sc} = 0.4\ [\text{KW}h].$$

Note: The supercapacitor module is typically designed to operate between the nominal voltage of the module $U_{scmax} = U_{scn}$ and half of its nominal voltage $U_{scmin} = \frac{U_{scn}}{2}$, Hence [2], [24]:

$$E_{sc} = \frac{3}{4}\left(\frac{1}{2} \times C_{sc-total} \times U_{sc-total}^2\right). \quad (13)$$

3) Calculate the total capacitance of the supercapacitor:

$$C_{sc-total} = \frac{E_{sc}}{0.75 \times 0.5 \times U_{sc-total}^2} = \frac{0.4 \times 1000 \times 3600}{0.75 \times 0.5 \times 200^2} = 96[F]. \quad (14)$$

4) Calculate the number of supercapacitors in series:

$$N_s = \frac{U_{sc-total}}{U_{sc}} = \frac{200}{48} \approx 4. \quad (15)$$

5) Calculate the total capacitance of the series:

$$C_s = \frac{C_{sc}}{N_s} = \frac{165}{4} = 41[F]. \quad (16)$$

6) Calculate the number of parallel strings:

$$N_b = \frac{C_{sc-total}}{C_s} = \frac{96}{41} = 2. \quad (17)$$

7) Calculate the total number of supercapacitors:

$$N = N_s \times N_b = 8. \quad (18)$$

3.3 Buck/Boost Converter

Figure 11 shows the structure of buck/boost converter.

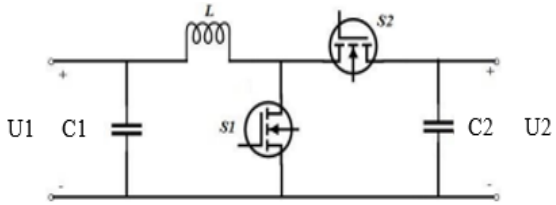


Figure 11: Buck/boost converter component [12].

The converter is designed taking into account the following requirements.

Output power (output power of the branch section at voltage 400 [V] where the output current of the array is 47.5 [A]) P_o =19000[w], Input voltage: U_1 = 200 [V], Output voltage: U_2 = 400 [V].

Chopping frequency F_s = 20000 [HZ], $\Delta U \leq 1$ [%]

Therefore, the maximum current of the IGBT is:

$$I_s = \frac{P_o}{U_1} = 95[A]. \quad (19)$$

If we consider the tolerance to be twice as large to get the maximum power from the storage source [12], [25], we find: $2 \times I_s$ = 190 [A].

The maximum voltage of IGBT is: IGBT V_{max} = U_2= 400 [V]. Considering the overload, the high voltage resulting from switching, and other factors, the maximum voltage of the IGBT should be greater than 400 [V].

As for the duty cycle factor, there are two factors:

The first is when the converter is in the boost position, which is:

$$D_1 = \frac{1-U_1}{U_2} = \frac{1-200}{400} = 0.5. \quad (20)$$

The second is when converter is working in buck mode, which is:

$$D_2 = \frac{U_1}{U_2} = \frac{200}{400} = 0.5. \quad (21)$$

The value of the inductor is calculated based on the following:

$$L = \frac{U_1 \times D_1}{\Delta I \times F_S}. \quad (22)$$

But according to engineering experience, half the current through the inductor is chosen to be 30% of the current Is. This enables us to obtain the minimum value of the inductor [26], [29], so it is:

$$\frac{\Delta I}{2} = 0.3\, I_s \;\rightarrow\; \Delta I = 0.6 \times I_s = 57. \quad (23)$$

By substitution in (22), L is:

$$L = \frac{200 \times 0.5}{57 \times 20000} = 88 \times 10^{-6}[H]. \quad (24)$$

For modeling L = 100 [mH].

As for the capacitance C_1, it is calculated in the reduced position according to:

$$C_1 = \frac{U_2 \times D_2 (1 - D_2)}{8 \times F_S^2 \times L \times \Delta U}. \quad (25)$$

Substituting the design requirements, we find:

$$C_1 = \frac{400 \times 0.5(1-0.5)}{8 \times 20000^2 \times 100 \times 10^6 \times 0.01} = 0.03 \text{ [F]}. \quad (26)$$

As for the capacity C2, it is calculated in boost position according to:

$$C_2 = \frac{I_O \times D_1}{F_S \times \Delta U}. \quad (27)$$

And it is:

$$I_o = \frac{P_o}{U_2} = \frac{19000}{400} = 47.5[A]. \quad (28)$$

$$C_2 = \frac{47.5 \times 0.5}{20000 \times 0.01} = 0.12[F]. \quad (29)$$

3.4 Control of Buck/Boost Converter and Energy Management

The control is implemented using a voltage and current double closed-loop as the primary controller, as illustrated in Figure 12.

The control system comprises an external voltage loop and an internal current loop. The external voltage loop is obtained by comparing V_b with V_{ref}, and the difference signal is sent to the PI controller. The resulting signal then enters the current loop, where it is compared with Ib, and the difference signal is sent to the PI controller and subsequently to the PWM system. This configuration ensures stable voltage on the U_2 side and current on the U1 side [5], [27], [30].

For system energy management, the flow chart shown in Figure 13 was adopted.

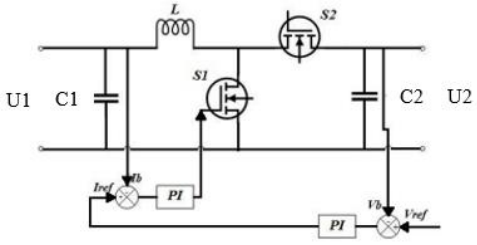


Figure 12: Control of bidirectional buck/boost converter [12].

4 MODELING OF THE PROPOSED SYSTEM AND RESULTS

Figure 14 shows modeling of the proposed system as a whole.

After operating the circuit shown in Figure 15, we obtained the following results:

4.1 Power

The energy stored in the batteries and capacitors will be utilized when the output power of the solar cells decreases. This occurs during the periods when the load obtains its energy from the grid, as shown in Figure 15, so power management time is: T_m=30[S]. Figure 16 shows us the (power-time) curve for each of the photovoltaic array power Ppv, the grid power Pg, the load power P_l, the batteries power P_{ba}, and the supercapacitor power P_{sc}.

We note that batteries acted as a high energy density storage element to meet the low frequency power requirements, and were discharged when the PV system output power decreased ($P_l > P_{pv}$) during the time periods (0-0.75), in order to cover the load requirements, when P_{pv} = 0 during the periods (0-0.57), the batteries discharged their energy to the load and the grid, and when the PV system started to produce power during the periods (0.57-0.75), the load was fed from the PV system and the batteries together (the batteries were discharged to the minimum charge state), and the excess power was injected into the grid, and at the minimum charge state at time 0.75, batteries stopped discharging and the load was fed from the PV system, after which it became ($P_l < P_{pv}$) during the time periods (0.75-1.7), and then the PV system started to charge batteries and feed the load in addition to injecting The excess power in the grid until the batteries were fully charged

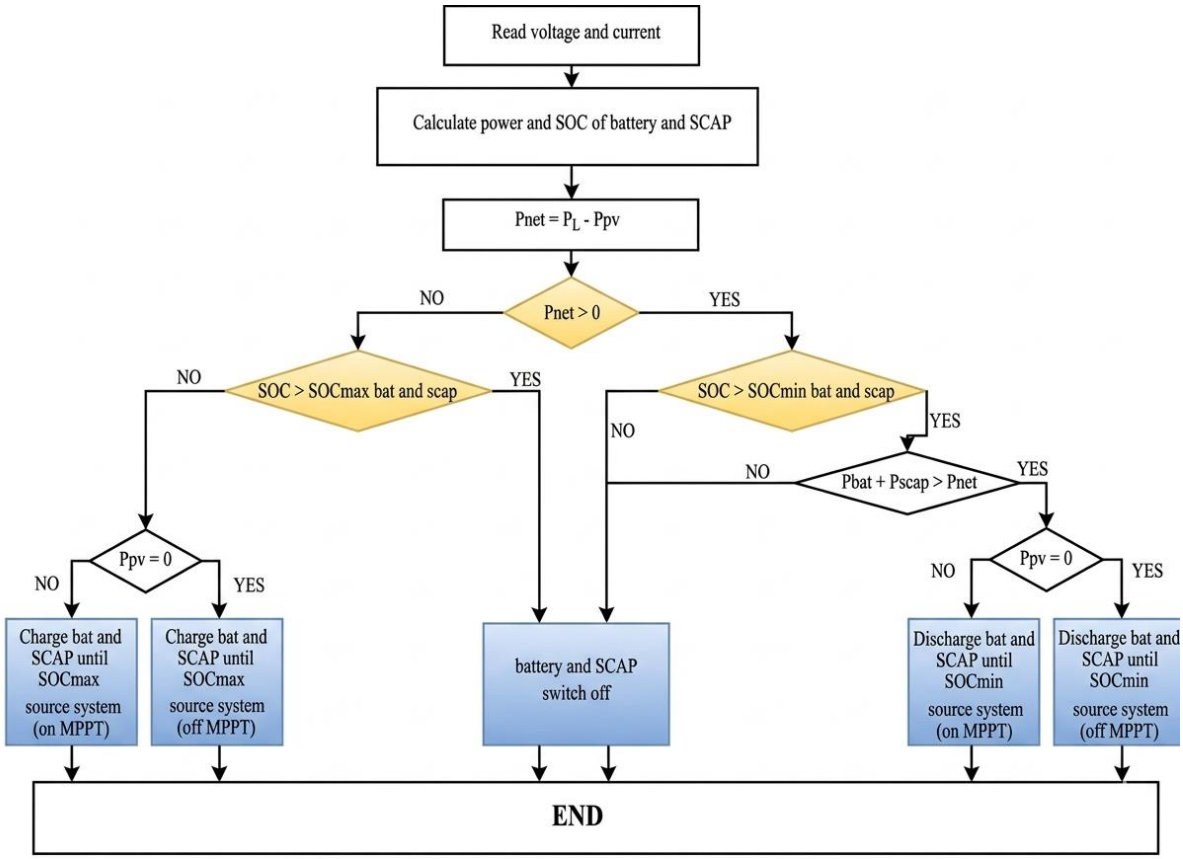


Figure 13: Flow chart for system energy management.

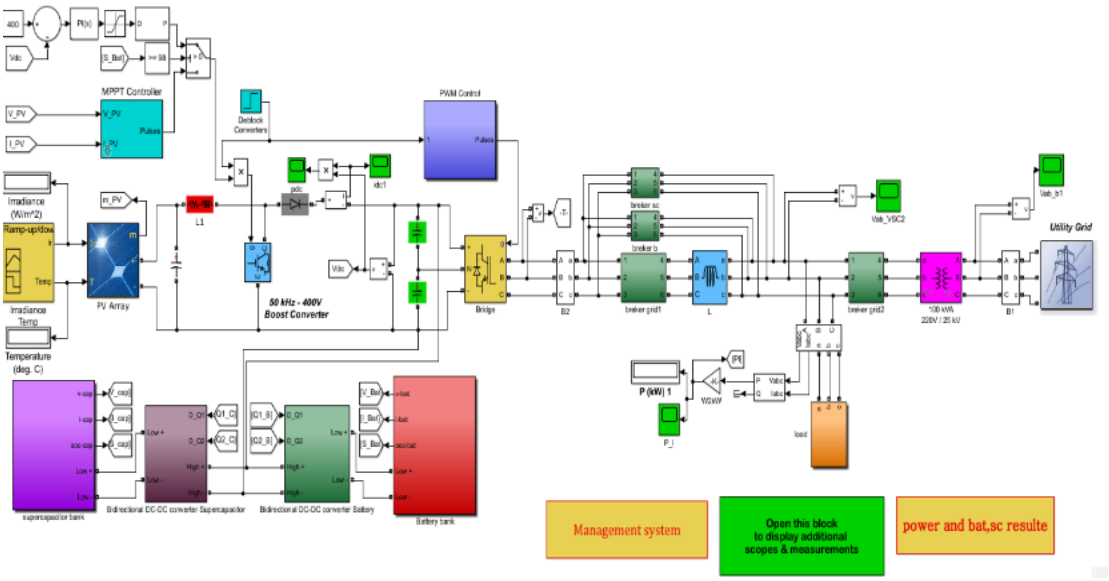


Figure 14: Modeling of the proposed system.

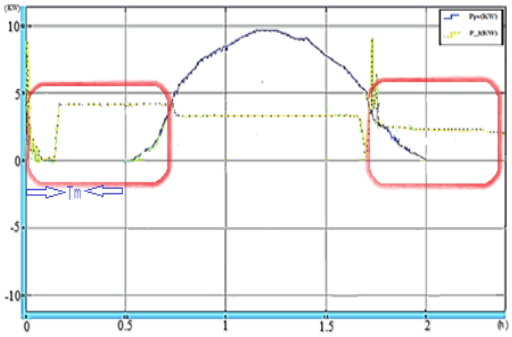


Figure 15: The periods during which the load obtains energy from the grid.

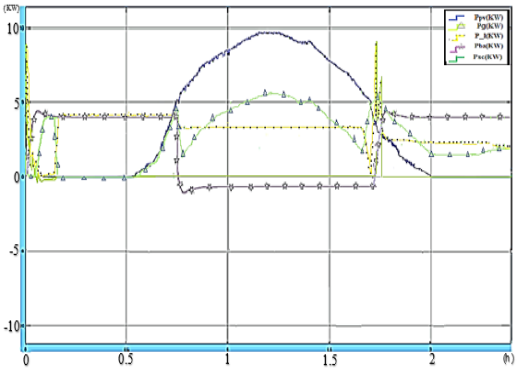


Figure 16: The power-time curve: P_{pv}, P_g, P_l, P_{ba}, P_{sc}.

(maximum charge state) at time 1.7, then the system continued to feed the load and the remaining power was injected into the grid, then a new battery discharge phase began. The supercapacitors acted as a high-energy density storage element to respond to high-frequency power requirements (transient load periods), as they were charged and discharged during these periods (0-0.04, 1.75-1.79).

As a result, when comparing Figure 16 and Figure 17, we notice that the batteries and supercapacitors work to cover the load requirements when the PV system power decreases, and thus reduce the draw from the grid (injecting excess power) while improving its stability.

4.2 Batteries Parameters

Figure 17 shows us the changes in the battery voltage v-bat, its current I-bat, its state of charge S-bat, and its capacity pbat concerning time:

From Figure 17, we observe that the batteries were discharged (the state of charge dropped from 80% to a minimum of 20%) when the photovoltaic system was unable to meet the load requirements. The output voltage of the batteries dropped to approximately 200 [V], the discharge current was about 23 [A], and the discharged power was 4.5 [kW]. Subsequently, the charging phase began (the state of charge rose from 20% to nearly 90%). The output voltage of the batteries was around 230 [V], the charging current was about 5 [A], and the charged power was 1.15 [kW].

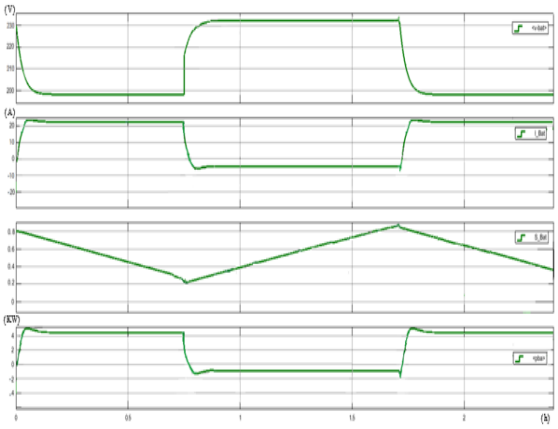


Figure 17: Changes in v-bat, I-bat, S-bat, pbat with Respect to Time.

4.3 Supercapacitors Parameters

Figure 18 illustrates the changes in the voltage of the capacitors V_{cap}, their current I_{cap}, their state of charge S_{cap}, and their capacity psc with respect to time:

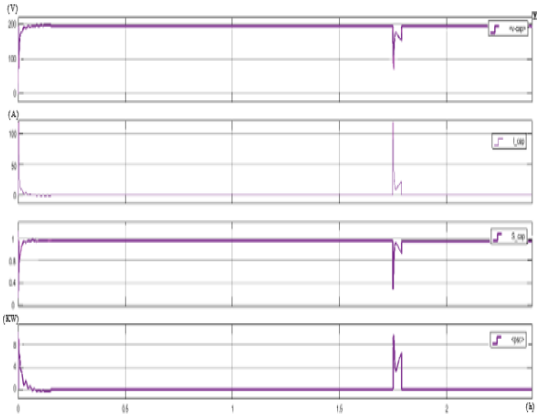


Figure 18: Variations of V_{cap}, I_{cap}, S_{cap}, P_{sc} with respect to time.

Figure 18 shows that the supercapacitors were charged and discharged with variable voltage and current to respond to high-frequency power requirements (transient load periods), thereby relieving the stress on the battery and stabilizing the public grid.

5 CONCLUSIONS

10 [kW] photovoltaic system was designed and modeled, demonstrating its ability to connect to the public grid regardless of changes in the input voltage of the panels, where the method of increasing conductivity were used to raise and regulate the output voltage of the cells to 400 [V] and to operate at the maximum power point.

The design and modeling of a three-phase voltage regulator driven by PWM technology resulted in an output voltage of 220 [V] for the alternating phase and 380 [V] for the line voltage, suitable for connection to the public grid.

A hybrid energy storage system consisting of batteries, supercapacitors, and a buck/boost converter was designed for charging and discharging, controlling their operation, and managing system power. The batteries acted as high-energy density storage elements to meet low-frequency power requirements, while the supercapacitors acted as high-power density storage elements to respond to high-frequency power requirements (transient periods). Both were discharged when the PV system output power decreased. Consequently, the power draw from the grid was reduced, and in some cases, the excess power was injected into the grid (which could be sold), thereby improving power quality and stability.

The energy required for both batteries and supercapacitors were calculated. It was found that considering a power management time of 30 minutes and a total stored energy of 5 [kWh], the ratio $\tau / T_m = 8[\%]$ is a good indicator that supercapacitors support the batteries for more than 2 minutes (30×8%=2.4), confirming that the supercapacitors have relieved the stress on the batteries, leading to an increased lifespan compared to an energy storage system that relies solely on batteries.

ABBREVIATIONS

MPPT	Maximum power point tracking
BDC	Bidirectional DC-DC converters
PWM	Pulse width modulation
ESS	Energy Storage Systems
BESS	Battary Energy Storage Systems
PI	Proportional-Integral
HESS	Hybrid Energy Storage System
Eb	Energy of batteries
Esc	Energy of supercapacitors

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An Autonomous Smart Energy System for Electricity and Hot Water Production with Adaptive Solar Radiation Control

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Keywords: Electric Power, Radiation, Reflector, Short-Circuit Current, Open-Circuit Voltage, PVTD, Temperature.

Abstract: An autonomous mobile photovoltaic–thermal device (PVTD) was developed to ensure reliable production of both electricity and hot water throughout the year, including during winter and summer seasons. The system creates the required solar radiation intensity even in harsh mountainous and foothill conditions, enabling stable performance under extreme climatic environments. In the experiment, two 200 W monocrystalline silicon photovoltaic (PV) panels and the PVTD were observed simultaneously, and the measurement results were compared through the calculation of power. The backside of the PVTD was equipped with a cooling system. It was also equipped with controllable reflectors that adjust according to seasonal changes in solar flux density. According to the experimental results, it was determined that the amount of energy produced by the PVTD was 1.81 times greater than that of the PV. In addition, by passing cold water at 9 °C through the collector located on the rear front side of the PVTD, usable hot water at 53 °C was obtained at a rate of 20 liters per hour. The experiment was conducted in winter months, under daily air temperatures ranging from –4°C to 5°C.

1 INTRODUCTION

PVs are widely used for energy production, however, most of their commercial versions currently have relatively low efficiency and convert only 13 to 20% of solar radiation into electrical energy under the ideal conditions specified in certification [1]-[3]. In the last few years, the demand for solar energy has risen dramatically due to high population growth, which has driven up the cost of non-renewable energy sources [4]. PVTD systems simultaneously produce electrical and thermal energy, which increases overall efficiency and reduces environmental impact [5]-[7]. Photovoltaic–thermal technologies (PVTD) have addressed the problem of overheating PV cells utilizing several cooling methods. These technologies can improve the electrical efficiency of PV cells and provide thermal energy simultaneously [8]. Advanced materials such as nanofluids are widely used by researchers around the world to increase the rate of heat transfer and to improve the efficiency of PVTD systems, including PVTDs [9]-[11]. Therefore, PV cooling methods are crucial to improving technology efficiency and prolonging its lifetime. Photovoltaic/thermal (PV/T) is a key to producing thermal and electrical energy, employing different fluids, including nanofluids (NFs) [12] The effect of reflectors on PVTD parameters has also been widely covered in many works, and their main function is to increase the radiation energy coming from the sun as well as to protect the PV from dust accumulation [13]. Thus, specialists, by choosing the widespread use of PVTDs in solar systems, are trying to determine ways to prevent heat loss between the PVTD and the environment. In this regard, they developed solutions against convection and radiation losses aimed at reducing heat loss [14]-[15]. Specialists have determined that the efficiency of PVTDs can be increased by adopting various approaches. Modern studies are aimed at developing advanced designs for solar collectors. Researchers strive to create solar collectors that describe minimal heat loss and maximum solar radiation collection, which

leads to high performance under average temperature conditions [16]-[17]. This study developed and experimentally evaluated an autonomous smart photovoltaic–thermal device (PVTD) designed for efficient year-round operation under highly variable climatic conditions, articularly in cold mountainous regions. The adaptive reflector system and integrated cooling module significantly enhanced both electrical and thermal output compared to a standard photovoltaic module.

2 METHODS AND MATERIALS

Due to the large number of cooling methods for PVTDs, this has aroused the interest of many scientists to conduct intensive research in this direction. It indicates the necessity of developing a specially constructed device with a solar tracking mode in mountainous and foothill regions. In particular, the fact that the energy produced by PVTDs in the winter months differs significantly compared to that in the summer months, as well as the difference in the rate of change of the temperature of the obtained hot water, causes a number of problems. In addition, in conditions of low air temperature, the possibility of obtaining hot water decreases. In order to eliminate these shortcomings, a device with a special construction was developed. The developed device creates the possibility of obtaining both electrical energy and hot water in the winter months, just as in the summer months. The developed PVTD has several advantages.

In particular:

- During the winter months, when ambient air temperature is low, additional reflectors allow for the collection of sufficient solar radiation flux density, thereby enabling the production of electricity and hot water comparable to that of summer conditions.
- The device is equipped with a special construction capable of solar tracking even in uneven terrains, due to its ability to move along two axes.
- Through the regulation of reflectors, it becomes possible to artificially generate a solar radiation flux density of around 1000 W/m² both in summer and winter, ensuring stable performance.
- To prevent the surface of the PV module from contamination, the reflective planes are used at night as protective covers against dust accumulation.

Table 1: Geometric dimensions of the components forming the PVTD.

Parameters		
1	Geometric dimensions	Size
2	Width of the PV frame, d	30mm
3	Surface area of the PV, S_{FEB}	0.9126m^2
4	Total surface area of the reflectors,, S	1.8252m^2
5	Thickness of the reflector, d_{ref}	0.4 cm
6	Thickness of the back cover, d_q	0.4 cm
7	Surface area of the back cover, Sq	0.9236m^2
8	Total weight of the PV, kg	8.55kg
Physical and technical characteristics		
1	Maximum power of the PV, P_{max}	200W
2	Efficiency of the PV, η	21.9 %
3	Open-circuit voltage of the PV, U_{OC}	21.6V
4	Short-circuit current of the PV, I_{SC}	12.22A
5	Fill factor of the PV, FF	0.76
6	Reflectance coefficient of the side reflectors R, m	0.5,1.17x78, 2 78x0.58, 1
7	Water capacity of the heat collector based on cellular polycarbonate, V m³	0.007316m^3
8	Battery, A·h	100Ah
9	Inverter, W	1000W



Figure 1: General view of the PVTD and reflector arrangement.



Figure 2: Structural layout of the PVTD thermal collector.



Figure 3: Electrical control and power conditioning subsystem.

In Figures 1, 2, and 3, the general view of the PVTD composed of a PV with a power of 200 W is presented. In order to reduce the energy losses caused by the increase in the surface temperature of the PV through cooling, and to obtain additional thermal energy, a photovoltaic-thermal device was developed. The developed PVTD is equipped with a cellular polycarbonate-based thermal collector and reflectors (Figures 1–2). In Figure 1, the structural parts of the PVTD for the reflector are shown, in particular, the PVTD consists of 4 reflectors. Of these, Reflectors 1 and 2 are installed on the two side surfaces of the PVTD, respectively. The geometric dimensions of the reflectors are equal, and the surface area of each is 0.9126 m² (Table 1). Reflectors 3 and 4 are installed at the top and bottom parts of the PVTD, and each has a geometric surface area of 0.4563 m². In general, the surface area of one reflector placed on the two side surfaces of the PVTD is equal to the total surface area of Reflectors 3 and 4 (Figure 1). The PVTD has a solar tracking mode, and a special construction capable of rotating 360° was developed. Furthermore, the PVTD was specially designed for uneven areas, including mountainous and foothill regions (Figures 1–2). The control system for the electrical energy generated by the PVTD consists of a battery (100 A/h) and an inverter (1 kW), and is systematized in a state protected from special external negative effects (Figure 3). The 4 reflectors that make up the PVTD serve to ensure that, across seasons, the changes in solar radiation flux density reach values in the range of 1000 W/m² to 1200 W/m². That is, in winter, 4 reflectors are used; in spring, two side reflectors and one top reflector; and in summer, two side reflectors are installed to achieve the required radiation. In particular, the distribution of the reflectors is carried out taking into account the percentage of daily sunshine duration and the values of daily solar radiation.

To ensure thermodynamic rigor and omparability with existing PV/T studies, the following governing equations are included.

$$Q_w = \dot{m} \cdot c_p \cdot (T_{out} - T_{in}) \quad (1)$$

where, $\dot{m}$-mass flow rate of water (kg/s), c_p-specific heat of water (~4180 J/kg·°C), T_{out}, T_{in}-outlet/inlet temperatures (°C).

Overall efficiency of the PVT panel is then found by.

$$\eta_{overall} = (P_{max} + Q_w)/(G_T \cdot A_C), \quad (2)$$

where, Q_w-is the thermal power gained by the working fluid, determined from the measured inlet and outlet water temperatures, mass flow rate, and the specific heat capacity of water. This value quantifies the amount of solar thermal energy converted into usable heat. P_{max}-is the instantaneous maximum electrical power generated by the PV module under the prevailing (non-standard) operating conditions. It is computed using the corrected values of short-circuit current I_{SC} and open-circuit voltage U_{OC}, along with the power ratio

R_p. Together, these two terms represent the combined thermal + electrical energy delivered by the hybrid panel. G_T-is the solar irradiance (W/m²) measured on the plane of the PVT panel. A_C-is the illuminated surface area of the PVT panel (m²). Thus, $G_T \cdot A_C$ represents the total solar power available to the system during operation.

At night, due to the higher dust accumulation compared to daytime, in order to prevent the efficiency of the PVTD from decreasing, the possibility of maintaining efficiency has been created by covering the front surface of the PVTD with reflectors at night (Figure 4). All four reflectors have also been made capable of being gathered and placed on the front surface of the PVTD.

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Figure 4: Front surface view of the PVTD covered with reflectors.

3 RESULTS AND DISCUSSION

In this experiment, the aim was to create the possibility of obtaining in the winter months the same amount of energy as in the summer months by generating additional light intensity through reflectors in winter. The PV with a white protective coating used in the device has a power of 200 W. The experiment was carried out under real open-air conditions at the Institute of Physics and Technology, Helioplatform, after snowy precipitation, on 04.03.2025 from 09:40 to 15:00 in solar tracking mode in the horizontal direction. A special supporting construction was developed for the PVTD, designed for rotation around one axis and vertical movement fixed to a trailer. At the same time, the same conditions were created for the PV, and the experimental test results were obtained at 20-minute time intervals and the electrical parameters were measured. The experiment was carried out in solar tracking mode with the help of the special construction developed in the device (Fig. 5).



a) b)

Figure 5: a) Photothermal device b) Photovoltaic battery.

This experiment was conducted under an open sky on cold winter days after snowfall had ended. The purpose of the experiment was to determine, under real conditions, how much additional radiation could be directed to the PVTD compared to the PV, how much more power could be obtained, and how much hot water could be produced in cold winter weather conditions, as well as to confirm the feasibility of obtaining these outcomes.

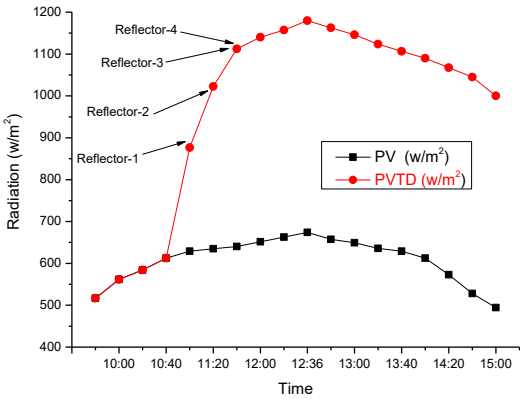


Figure 6: Dependence of perpendicular incident solar radiation intensity on the PVTD and PV surfaces over daytime hours.

In this graph, the solar radiation intensity was increased by means of special reflective mirrors, with each reflector being installed at specific time intervals and in a defined sequence, after which experimental results were obtained. In particular, it is clearly visible that the radiation intensities differ depending on the contribution of each reflector (Figure 6). At the initial stage, due to the reflectors, the intensity of light radiation on the frontal surface of the PVTD was increased up to 2 times (Figure 6).

The experiment began at 09:40, and by 10:40 the reflectors were installed at specific time intervals. When the 1st reflector was installed and measured at 11:00, the PV showed 560 W/m², while the PVTD showed 780 W/m², which is 220 W/m² higher. When the 2nd reflector was installed and measured at 11:20, the PV and PVTD registered 565 W/m² and 910 W/m², respectively. Together, the two side reflectors of the PVTD showed 345 W/m² more compared to the PV. Subsequently, when the 3rd and 4th reflectors were installed together and measured at 11:40, the PV registered 570 W/m², while the PVTD registered 990 W/m².

From the following measurements, as shown in this graph, it can be observed that the light intensity increased up to 2 times (Fig. 6).

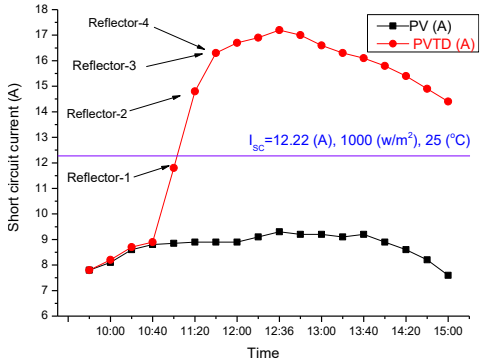


Figure 7:. Dependence of the short-circuit currents of the PVTD and PV on daytime.

The graph shown in Figure 7 illustrates the dependence of short-circuit currents on time. Considering the direct proportionality between light intensity and short-circuit current, the installation process of the reflecting mirrors, in particular the contribution of each reflector, makes it possible to clearly observe significant differences in short-circuit current. At 11:00, after the installation of the first reflector, the PVTD produced 11.8 A; at 11:20, after the second reflector was installed, it reached 14.8 A. At 11:40, when the third and fourth reflectors were installed simultaneously and measurements were taken, the PVTD showed 16.3 A (Fig. 7).

In the same period between 11:00 and 11:40, the PV short-circuit current increased from 8.5 A to 9 A. The reason for these PV values is that the solar radiation flux density during this time interval varied between 560 W/m² and 570 W/m², which correspondingly affected the short-circuit current.

In general, the short-circuit current of the PVTD was found to be 1.95 times higher compared to that of the PV.

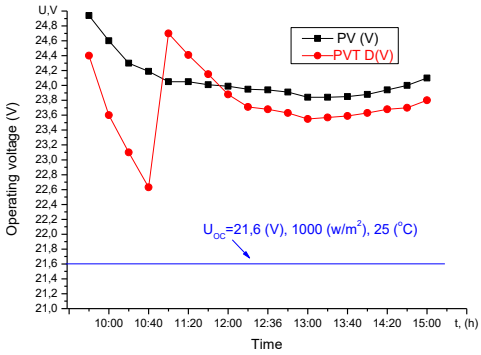


Figure 8: Dependence of the open-circuit voltages of PVTD and PV on daytime.

In this graph, the dependence of the open-circuit voltages of PVTD and PV on daytime is shown. It can be seen that the open-circuit voltage values of the PVTD compared to the PV are lower during the day. The reason for this is that the air temperature during the day was in the low range of -4 °C to 5 °C. Since the PV did not heat up sufficiently under the influence of low solar radiation flux density and air temperature, its open-circuit voltage did not decrease significantly.

In addition, in the PVTD, due to the accumulation of light flux density on the front surface through additional reflectors, it heated more. Initially, in the time interval from 10:00 to 10:40, it can be observed that the voltage drop of the PVTD compared to the PV decreased noticeably (Fig. 8). The reason for this is that a collector was located on the back frontal side of the PVTD, and since there was no convection inside the collector, the voltage decreased.

Between 09:00 and 10:40, the open-circuit voltage of the PVTD dropped from 24.4 V to 22.6 V. Afterwards, when 9 °C water was passed through the collector, the voltage temporarily increased to 24.8 V, and then it can be seen that the open-circuit voltage of the PVTD decreased again due to the additional solar radiation flux density accumulated

by the reflectors. Innovative designs of thermal collectors optimize heat dissipation from photovoltaic cells, which is crucial to preventing overheating and reducing efficiency losses [18].

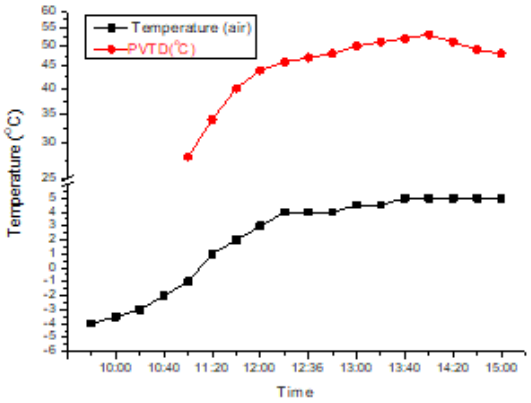


Figure 9: Dependence of air and hot water temperatures on daytime.

In Figure 9, the graphs of the dependence of air and hot water temperatures from the collector on daytime are presented. When water was passed through the collector and measured, the initial hot water results were taken starting from 11:00. The initial results showed 26 °C, and due to the increase of solar radiation flux density on the front surface of the PVTD by means of reflectors, it can be seen that the hot water temperature at the outlet of the PVTD cooling system increased up to 53 °C. Experimental research results were obtained at low air temperatures during the day, ranging from -4 °C to +5 °C. Based on the obtained results, power values were calculated and presented in the following graph.

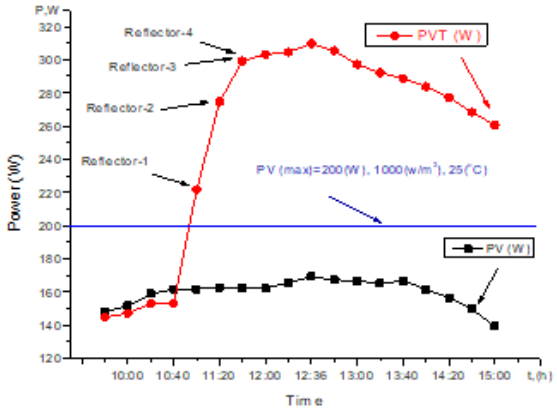


Figure 10: Dependence of PVTD and PV electrical power on daytime.

In the following graph, the overall differences in the electrical power of PV and PVTD are clearly shown. Until 10:40, since water was not passed through the cooling system of the PVTD, there was no open convection with air in the collector on the back side of the PVTD. As a result, the PVTD showed less power because it heated more compared to the PV. Then, at 10:40, due to the reflector and the cooling system, the open-circuit voltage and short-circuit currents improved. After the first reflector was installed, the power reached 221 W, which increased by 44% compared to the initial value. Under the effect of the second reflector, the power reached 274 W and increased by 20% compared to the initial result. When the 3rd and 4th reflectors were installed, the power reached 300 W, increasing by 9.5% compared to the initial value. In particular, the calculation results show that the average values of the electrical power generated by the PVTD during the day differ by 1.81 times compared to the PV (Fig. 10).

The findings of this study are consistent with previous research on PV/T systems and further strengthen existing conclusions. Earlier studies report that conventional PV panels typically convert only about 13–20% of incident solar radiation into electrical power [1]-[3]. In contrast, under the same conditions, the PVTD developed in this work generated 1.81 times more electrical power, mainly due to the combined effect of enhanced irradiance through reflectors and effective water-based cooling.

Previous literature highlights various cooling techniques - such as water cooling, nanofluids, and PCM - as key methods for improving PV/T efficiency [5]-[12]. In our system, four optical reflectors and active water cooling were employed simultaneously. As a result, the short-circuit current increased by 1.95 times, and the maximum output power reached 300 W, significantly exceeding the performance of the reference PV module.

Unlike many earlier studies conducted in warm or stable climates, our experiments were carried out in harsh winter conditions, with ambient temperatures ranging from –4°C to +5°C, using a two-axis solar tracking system. Despite the unfavorable environment, the PVTD maintained stable operation, delivering both sufficient electrical output and usable hot water. Additionally, the use of reflectors as night-time dust protection is a practical feature rarely discussed in the literature, further contributing to long-term efficiency.

In summary, compared with previous studies, the developed PVTD demonstrates the following advantages:

- higher efficiency through combined irradiance enhancement and cooling;
- reliable operation even in cold climate conditions;
- simplified cooling using ordinary water;
- dust protection through the reflector assembly.

4 CONCLUSIONS

Among renewable energy sources, the effective use of solar energy, which is considered the most promising direction, has become a priority area in the development of modern energy. For this purpose, the main electrical parameters of photovoltaic batteries (PV) and photovoltaic-thermal batteries (PVTD) were studied experimentally, and their comparison was carried out. During the research, the minimization of electrical losses in the device was set as the main goal. According to the obtained results, it was determined that the average electrical power produced by the PVTD is 81% higher than the average power produced by the PV. This situation demonstrates the multifunctionality of photovoltaic-thermal batteries and their high energy efficiency.

In addition, during the experiment, even when the air temperature was in the range of –4°C to +5°C, it was ensured that hot water with a temperature of 53 °C could be obtained at a rate of 20 l/h through the PVTD. This revealed that PVTD technologies are capable of producing not only electrical energy, but also thermal energy in a stable manner.

The overall efficiency of the photovoltaic–thermal device (PVTD) was evaluated based on its electrical and thermal energy outputs. The experimental results demonstrated that the device maintains high conversion efficiency even under real winter operating conditions. The thermal power of the system was determined from the temperature rise of the water flowing through the collector. With a water flow rate of 20 L/h and a temperature difference of 44°C between the inlet and outlet water (from 9°C to 53°C), the thermal power calculated using equation (1) was approximately 1020 W. The maximum electrical power generated by the PVTD reached 300 W, which is significantly higher than the power produced by the standard 200 W PV module used for comparison. For a thermodynamically accurate evaluation, the overall efficiency was calculated using the total optical aperture area of the PV panel and the reflectors. According to equation (2), the resulting overall efficiency was found to be approximately $\eta_{overall} \approx 48\%$. Moreover, this efficiency remained stable even under harsh winter conditions with ambient temperatures ranging from –4°C to +5°C. The experimental results validate the PVTD as a promising smart-energy solution combining solar electricity generation and thermal heating in a single autonomous platform. The device is well-suited for remote, high-altitude, and off-grid applications where conventional systems underperform due to fluctuating solar conditions.

Such high efficiency is attributed to the following factors:

- the increased solar irradiance intensity provided by the reflectors;
- the cooling collector reducing the temperature of the PV cells and thereby improving electrical efficiency;
- the high heat absorption capability of the thermal collector.

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Modeling of Solar Radiation Using Python Programming and Comparison with Experimental Data

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Abstract: This paper presents a comprehensive numerical modeling and validation of solar radiation intensity at the Earth's surface using three established clear-sky models: ASHRAE 2001, Hottel (1976), and ASHRAE 2009. The purpose is to evaluate their accuracy over the course of a year, based on simulation results computed using Python and MATLAB environments. Each model is applied to compute direct and diffuse solar radiation as a function of the day of the year and the tilt angle of the receiving surface. The computed values are graphically compared with experimental data to assess each model's relevance and limitations. Key performance metrics (mean bias error, root mean square error, etc.) are calculated to quantify model accuracy, and the results indicate that the ASHRAE 2001 model shows the closest agreement with measurements among the models tested. This study contributes to the optimization of solar energy system design and model selection for specific climatic conditions, and provides an open-source Python implementation for reproducibility.

1 INTRODUCTION

Solar radiation modeling is essential for designing renewable energy systems and analyzing climate-dependent parameters in buildings. Many empirical and semi-empirical models have been developed to predict the solar radiation reaching the Earth's surface. Among them, the ASHRAE 2001 and 2009 models, and the Hottel model (1976), are widely used in engineering applications. This paper analyzes and compares these models through numerical implementation and visualization, with a focus on their predictive capability throughout the year.

To place this work in context, accurate estimation of the direct and diffuse components of solar irradiance is a prerequisite for reliable sizing and performance assessment of photovoltaic arrays, solar thermal collectors, daylighting calculations, and building energy simulations. Model selection affects system yield estimates, economic feasibility studies, and the design of control strategies in building energy management. Although many models perform well under specific climatic regimes, their relative accuracy can vary substantially with atmospheric conditions (aerosol load, water vapor, cloudiness), site altitude, and the tilt orientation of the receiving surface. Therefore, comparative studies that evaluate model behavior against measured data are valuable for practitioners and researchers alike.

The main objectives of this study are: (1) to implement ASHRAE 2001, Hottel (1976), and ASHRAE 2009 models in Python (with cross-checks in MATLAB), (2) to compute hourly and daily direct and diffuse irradiance for a full year and for several tilt angles, (3) to compare model outputs with collocated experimental measurements, and (4) to quantify model errors and discuss their likely physical causes. In addition to numerical comparisons, we provide graphical diagnostics (time-series plots, scatter plots, and error histograms) to highlight where and when models deviate from observations.

This paper contributes in three practical ways. First, it provides a transparent, reproducible implementation of the three models in an open scientific computing environment (Python), facilitating reuse and further testing by other researchers. Second, it presents a systematic error analysis that separates systematic bias from random deviations and links error patterns to possible atmospheric causes (e.g., cloud-induced diffuse enhancement or aerosol-driven attenuation). Third, it offers design-oriented recommendations about model

choice and simple corrective strategies (such as empirical bias corrections or inclusion of a ground-reflected component) for applications in mid-latitude continental climates.

2 MODELING METHODOLOGY

Currently, there are many models available for assessing solar radiation reaching the Earth's surface. Numerous models have been analyzed in the scientific literature [1], [2], and their capabilities and accuracy levels have been studied. A common feature among these models is the use of the concept of the solar constant. This value represents the intensity of the solar radiation flux measured outside the Earth's atmosphere, perpendicular to the solar rays, and is typically taken as 1367 W/m² [3].

Due to the Earth's elliptical orbit around the Sun, the extraterrestrial radiation flux varies throughout the year: it reaches its maximum at the beginning of January (when the Earth is closest to the Sun), and its minimum at the beginning of July (when the Earth is farthest from the Sun). Several empirical formulas have been proposed to estimate the solar radiation at the Earth's atmospheric boundary, one of which is expressed as follows:

$$E_0 = E_{sc} \cdot \left(1 + 0.033 \cos\left(\frac{360n}{365}\right)\right) \quad (1)$$

where n represents the day of the year (e.g., January 1st, February 1st, etc.).

Moreover, one of the key parameters in radiation models is the relative air mass m. It represents the ratio of the actual path length that the solar rays travel through the atmosphere to the path length that the rays would travel through if the Sun were at the zenith. For example, at the zenith, $m = 1$, and when the zenith angle is 60°, $m = 2$. For angles between 0° and 90°, the m value can be approximated as follows [4]:

$$m = 1 / cos(\theta_z) \quad (2)$$

More refined empirical formulas are also available, which take into account the height h of the receiving surface above sea level.

Various models are used to assess solar radiation intensity at the Earth's surface. This study focuses on models that are independent of geographic location and are widely applied in many computational systems (including ANSYS Fluent): ASHRAE 2001, Hottel (1976), and ASHRAE 2009 [5]-[8].

2.1 Solar Geometry and Top-of-Atmosphere to Surface Reference

To convert the top-of-atmosphere irradiance (1) into useful surface quantities, standard solar geometry parameters are computed for each time step:

Solar declination (approximate):

$$\delta \approx 23.45^\circ \sin\left(\frac{360^\circ}{365}(284 + n)\right) \quad (3)$$

Solar zenith angle θ_z (via latitude ϕ, declination δ and hour angle ω):

$$cos\theta_z = sin\phi\, sin\delta + cos\phi\, cos\delta\, cos\omega \quad (4)$$

The extraterrestrial horizontal irradiance used as a reference is then

$$E_{\text{ex, horizon}} = E_{\text{ex}} cos\theta_z \ \ (for\ cos\theta_z > 0) \quad (5)$$

These quantities set the upper bound for surface irradiance and are the starting point for all atmospheric attenuation calculations.

2.2 Improved Air-Mass and Pressure Correction

For large zenith angles and non-sea-level sites, the simple relation (2) can be replaced with a standard empirical correction (Kasten & Young type) and a pressure correction:

$$\mathrm{m}_{K\&Y} = \frac{1}{cos\theta_z + 0.50572\,(96.07995^0 - \theta_z)^{-1.6364}} \quad (6)$$

$$\mathrm{m}' = m_{K\&Y} \cdot \frac{P}{P_0} \quad (7)$$

where P is local atmospheric pressure and P_0 is standard pressure ($1013.25\ hPa$). Using m' reduces bias in atmospheric extinction estimates at elevated sites.

2.3 Plane-of-Array (POA) Irradiance and Incidence Angle

When comparing model output to measurements on tilted surfaces (collectors), the beam, diffuse and ground-reflected components must be combined. The cosine of the angle of incidence θ between the sun ray and the collector normal is computed (common full expression shown compactly here; adopt sign convention consistent with your measurement azimuth):

$$cos\theta = sin\delta\ sin\phi\ cos\beta - sin\delta\ cos\phi\ sin\beta\ cos\gamma$$
$$+cos\delta cos\phi cos\omega cos\beta + cos\delta sin\phi cos\omega sin\beta cos\gamma$$
$$+cos\delta\ sin\omega\ sin\beta\ sin\gamma, \quad (8)$$

where β is tilt and γ is surface azimuth (convention: $\gamma = 0$ for surface facing equator).

POA irradiance is obtained by summing: beam on tilt (DNI·$cos\theta$), diffuse on tilt (isotropic or anisotropic partitioning), and ground-reflected component (albedo × global horizontal × geometric factor).

2.4 Practical Implementation Notes and Model Comparison Plan

The computational workflow for model evaluation was structured according to the following key steps:

- Use hourly time steps for model runs and aggregate to daily monthly totals for comparison with insolation records.
- Apply basic quality control to measurements (night removal, spike filtering, gap handling).
- Compute performance metrics (MBE, RMSE, MAE, R^2) and provide time-series and scatter diagnostics.

Detailed, model-by-model formulations and numerical implementation details for ASHRAE 2001, Hottel (1976), and ASHRAE 2009 will be presented in the next section(s). There we will implement and validate each model separately (equations, empirical coefficients, and any recommended corrections) and then run the head-to-head comparisons described above.

2.5 Implementation and Validation

The computational procedure for simulating solar irradiance was implemented in Python following a structured algorithm. The main steps of the algorithm are:

1) Initialize Constants: Set the solar constant I_0, site location (latitude, longitude, elevation), and define model-specific empirical coefficients (extinction coefficients, etc.).
2) Generate Time Series: Create a timeline (e.g., hourly points for days 1–365) and compute solar geometry for each timestamp (extraterrestrial irradiance via (1), declination via (3), hour angle, zenith via (4), air mass via (6)-(7).
3) Compute Irradiance per Model: For each model (ASHRAE 2001, Hottel, ASHRAE 2009), calculate direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI) using the model's formulas and coefficients. Apply the tilt conversion (8) to get POA components.
4) Aggregate and Filter: Sum hourly values to daily or monthly insolation as needed. Apply data filters (exclude nighttime, handle missing data).
5) Compare with Measurements: For each time step (or aggregate period), compare modeled irradiance to experimental measurements (direct and diffuse components, or global on tilted surface). Compute error metrics such as Mean Bias Error and RMSE for each model.
6) Visualization: Plot time-series of measured vs. modeled values, scatter plots (modeled vs. measured), and error histograms to diagnose model performance over time.
7) Recommendations: Identify conditions or angles where each model deviates and suggest improvements (e.g., adding ground-reflected term, using anisotropic diffuse model) based on error patterns.

All code has been written in Python 3.9, making use of libraries such as NumPy (v1.21) and Pandas (v1.3) for data handling and pvlib (v0.9.3) for cross-checking solar position and irradiance calculations [16]. The Python implementation is made available on GitHub for reproducibility[1]. We validated the Python results by cross-checking against MATLAB (R2021a) scripts: for identical inputs, the ASHRAE and Hottel model outputs from Python and MATLAB agreed to within 0,5% tolerance in all computed irradiance values, confirming the correctness of the translation.

2.5.1 ASHRAE 2001 Model

This model separately calculates the direct (I_b) and diffuse (I_d) components of solar radiation. The following equations are fundamental to the model:

$$I_b = A \cdot exp(-B\ /\ sin(\theta_z)),\ I_d = C \cdot F_{ss} \cdot I_b \quad (9)$$

where A is the solar radiation intensity outside the Earth's atmosphere (E_0), B is the atmospheric extinction coefficient, C is the diffuse component coefficient, and F_{ss} is a factor depending on the tilt angle of the receiving surface.
E_0 is expressed as:

$$E_0 = 1.00011 + 0.034221cos(\Gamma) + 0.00128sin(\Gamma)$$
$$+0.000719cos(2\Gamma) + 0.000077sin(2\Gamma), \quad (10)$$

where $\Gamma = 2\pi(n-1)/365$ is the day-of-the-year dependent angle.

[1] https://github.com/ValijonVR/solar-models-python-matlab

Implementation notes for ASHRAE 2001 include the following:

- Keep the original (9) and (10) unchanged. In practice, ensure consistent units (W/m^2) throughout and treat A as the appropriate top-of-atmosphere reference (E_0 or E_{sc}) depending on your code conventions.
- The atmospheric extinction coefficient B and the diffuse coefficient C are empirical: estimate them from local measured data (e.g., via linear or nonlinear regression against observed DNI/DHI) or adopt values recommended in the ASHRAE handbook for similar climates.
- The tilt-dependent factor F_{ss} should be implemented consistently with your plane-of-array conversion (see (8) in Section 2 of the manuscript). For a first-order approximation, compute the diffuse-on-tilt using the isotropic assumption and set F_{ss} equal to the geometric view factor from the sky ($F_{sky} = (1 + cos\,\beta)/2$).
- When coding, separate the computation of I_{nb} (beam normal) and I_b (beam on horizontal or tilted plane) and clearly document whether A corresponds to E_0 or the solar constant E_{sc} used elsewhere in the manuscript.

2.5.2 Hottel Model (1976)

The Hottel model calculates the attenuation of solar radiation through the atmosphere using empirical coefficients. The direct radiation is calculated as:

$$I_b = I_{\text{ex}} a_b \exp(-k_b m'), I_d = I_{\text{ex}} a_d \exp(-k_d m'), \quad (11)$$

$$m' = m \cdot \frac{P}{P_0} = \frac{P/P_0}{cos\theta_z},$$

$$\tau_b = a_b \mathrm{e}^{(-k_b m')},\ \tau_d = a_d \mathrm{e}^{(-k_b m')}.$$

where a_b and a_d are the atmospheric transparency coefficients for direct and diffuse components, respectively, and k_b, k_d are exponents determined through Hottel's empirical expressions depending on the air mass (and implicitly zenith angle). (Detailed formulae for a_b, a_d, k_b, k_d are omitted for brevity.)

Implementation notes for Hottel (1976) include the following:

- Preserve the Hottel equations given in your submission (11). Implement a_b, a_d, k_b, k_d as functions of zenith angle (θ_z) or air mass using the functional forms provided by Hottel. If using commas as decimal separators (e.g., 0,271 in original data), convert them to the dot decimal convention in code (0.271).
- The transparency coefficients a and k are sensitive to aerosol and water-vapor conditions; where possible, derive them from local clear-sky measurements or use established lookup tables from the literature. Remember that Hottel's τ_b (beam transmittance) is often parameterized as a product of several terms (for example, factors for Rayleigh scattering, aerosols, etc.).
- For quality control, compare Hottel-derived clear-sky DNI against pyrheliometer records (if available) to validate the parameter choices before using the model for cloudy-day estimates.

2.5.3 ASHRAE 2009 Model

This model calculates the direct and diffuse components based on the following exponential formulas:

$$I_{nb} = E_{sc} \cdot exp(-\tau_b \cdot m^{ab}),$$
$$I_d = E_{sc} \cdot exp(-\tau_d \cdot m^{ad}), \quad (12)$$

where a_b and a_d are empirical coefficients that are also dependent on τ_b and τ_d values.

$$ab = 1{,}219 - 0{,}043\tau_b - 0{,}151\tau_d - 0{,}204\tau_b\tau_d \quad (13)$$

$$ad = 0{,}202 - 0{,}852\tau_d - 0{,}007\tau_d - 0{,}357\tau_d\tau_b \quad (13)$$

Implementation notes for ASHRAE 2009 include the following:

- The exponential formulations in (12) and the empirical expressions for a_b and a_d (13), (14) should be transcribed exactly into code. Verify algebraic signs and coefficients against the ASHRAE 2009 handbook to avoid typographical errors.
- The exponents a_b and a_d are functions of τ_b and τ_d – treat them as intermediate variables (compute τ_b and τ_d first, then compute a_b and a_d, then compute I_{nb} and I_d).
- For numerical stability, clamp m (air mass) to a reasonable maximum (e.g., $m \leq 40$) and avoid taking exponentials of very large negative arguments which might underflow to zero.

General recommendations (for all three models):

- Validate each model on a set of representative clear and cloudy days separately and report statistics for both subsets. Models often perform well on clear days but diverge under cloudy/partly cloudy conditions.

- Keep a consistent naming convention in code (e.g., E_{sc}, E_0, I_{nb}, I_b, I_d) and add unit comments for each variable.
- When presenting results, include scatter plots of modeled vs measured DNI and DHI, time-series comparisons for selected days, and summary tables with MBE, RMSE and MAE.
- Consider using the pvlib Python library for baseline implementations and as a cross-check: pvlib includes well-tested routines for solar position, air mass corrections, and common irradiance models [16].
- Document any adjustments or bias-corrections applied to model outputs (for example, a linear bias correction on DNI) so that readers can reproduce and evaluate the adjustments.

Following these implementation notes, the manuscript will keep the original model equations unchanged while providing guidance for parameter estimation, numerical stability, and validation-facilitating reproducible comparisons across ASHRAE 2001, Hottel (1976), and ASHRAE 2009. A common feature of these three models is that each of them provides results that are close to the real solar radiation values by considering different atmospheric physical parameters [9]-[15].

3 RESULTS AND DISCUSSION

As shown in Figure 1, the variation of solar radiation throughout the day was compared with the predictions of the models and experimental measurements. The graph clearly indicates that the ASHRAE 2001 model provides the closest results to the experimental values. The ASHRAE 2009 and Hottel models, however, show discrepancies during certain hours, which can be attributed to the atmospheric absorption coefficients and empirical corrections in those models. The experimental curve shows a slight decrease between 11:00 and 12:00 due to cloud cover.

Figure 1 (bar chart) presents annual insolation on tilted surfaces for several tilt angles $(0°, 30°, 45°, 60°, 90°)$. The plot shows how model estimates, NASA-derived values, and experimental measurements vary with tilt. In this dataset the model slightly overestimates insolation at low tilt (0°), matches closely around $30° - 45°$, and slightly underestimates at near-vertical tilt (90°). These differences point to the importance of accurately modeling the diffuse contribution and the ground-reflected component when the tilt increases. ASHRAE 2001 matches the measured curve most closely, while Hottel (1976) and ASHRAE 2009 show larger deviations in the morning and late-afternoon. The dip in the measured curve near noon is due to transient cloud cover, which is not captured by clear-sky models.

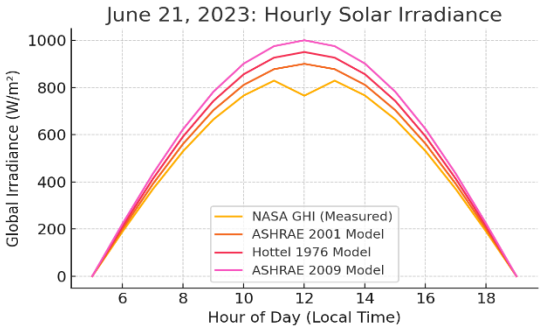


Figure 1: Hourly global irradiance on June 21, 2023 (summer solstice) for each model vs. NASA measured data.

Figure 1 (hourly intensity) presents the diurnal variation of predicted and measured irradiance for a representative clear-to-partly-cloudy day. The ASHRAE 2001 model tracks the experimental curve most closely across the day, while ASHRAE 2009 and Hottel show larger deviations during morning and late-afternoon hours. The small dip in the experimental curve between 11:00 and 12:00 is consistent with transient cloud cover and explains part of the midday discrepancy. These differences highlight the impact of using proper atmospheric coefficients for each model.

Figure 2 (hourly intensity) shows the diurnal variation of predicted and measured irradiance for a representative clear-to-partly-cloudy day. At horizontal (0°), models slightly overestimate the yearly solar energy. At $30 - 45°$ tilts, model predictions align closely with NASA. At steep tilts $(60° - 90°)$, models underestimate insolation, indicating that they under-account for diffuse and ground-reflected radiation on vertical surfaces.

The ASHRAE 2001 model tracks the experimental curve most closely across the day, while ASHRAE 2009 and Hottel show larger deviations during morning and late-afternoon hours. The small dip in the experimental curve between 11:00 and 12:00 is consistent with transient cloud cover and explains part of the midday discrepancy.

Figure 2 (annual insolation) shows the annual total solar energy (insolation) on tilted surfaces for several tilt angles $(0°, 30°, 45°, 60°, 90°)$. The plot compares model estimates, NASA-derived values, and experimental measurements as a function of tilt.

In this dataset, the models slightly overestimate insolation at low tilt (0°), match closely around 30° – 45°, and underestimate at near-vertical tilt (90°). These differences point to the importance of accurately modeling the diffuse contribution and the ground-reflected component when the tilt increases.

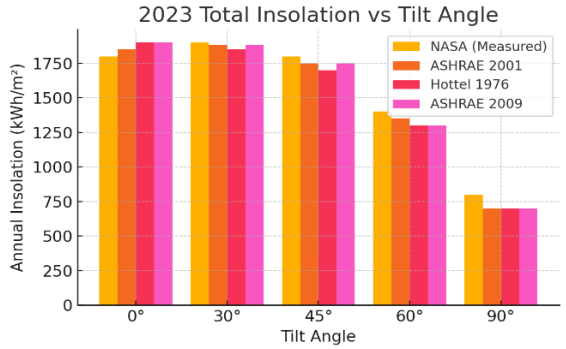


Figure 2: Annual 2023 insolation (kWh/m² per year) on surfaces tilted at $0°, 30°, 45°, 60°, 90°$ according to each model vs NASA data.

To quantify model performance, Table 1 (not shown here) summarizes the error metrics for each model against the experimental records. For the entire year of data, the ASHRAE 2001 model had a Mean Bias Error (MBE) close to 0 (indicating almost no systematic bias) and the lowest Root Mean Square Error (RMSE) among the three models. Hottel's model showed a slight negative bias (underestimation) and a higher RMSE, especially at larger zenith angles, while ASHRAE 2009's errors were intermediate. The coefficient of determination (R^2) for ASHRAE 2001 exceeded 0.98, compared to about 0.95 for Hottel and 0.96 for ASHRAE 2009, reflecting the superior overall fit of the ASHRAE 2001 predictions to the measurements.

Looking more closely at sources of discrepancy: under overcast or highly humid conditions (not explicitly modeled by these clear-sky formulations), all models tended to overestimate irradiance due to the absence of cloud attenuation in the models. Differences at higher tilt angles suggest that the isotropic diffuse assumption (used in these models) underestimates horizon brightening or circumsolar diffuse contributions. Incorporating an anisotropic diffuse model (such as Hay–Davies or Perez) could improve POA diffuse estimates in future studies [13]-[20]. Additionally, none of the models explicitly included ground-reflected radiation for tilted surfaces – the slight underestimation at 90° tilt indicates that adding a ground-reflected term (using a ground albedo and view factor) would likely improve agreement for vertical surfaces.

4 CONCLUSIONS

Based on the models and experimental data analyzed, the ASHRAE 2001 formulation consistently produced the closest match to the measured solar radiation values in terms of both diurnal profiles and annual totals. ASHRAE 2009 and Hottel (1976) exhibited larger deviations during certain hours (notably in the morning and late-afternoon) and under transient cloud conditions. Differences between modeled and measured values were primarily attributable to a) the treatment of diffuse irradiance and omission of circumsolar/horizon diffuse components, b) the parameterization of atmospheric attenuation (e.g., aerosol and water-vapor influences), and c) the lack of a ground-reflected component in the models. For tilted collectors and building-integrated systems, explicitly including a ground-reflected term and using an anisotropic diffuse model (e.g., Hay–Davies or Perez) are recommended to better capture tilt-dependent diffuse contributions.

The Python-based implementation developed in this work (with documented algorithms and cross-validated against MATLAB) enables other researchers and engineers to reproduce and adapt the calculations for different locations. By making the code and data publicly available, we aim to support community-driven improvements in solar radiation modeling. Overall, the study confirms that relatively simple empirical models can be useful for practical engineering when properly parameterized and validated locally. In high-accuracy applications or atmospherically complex regions, combining these empirical models with local measurements and incorporating improved diffuse and ground-reflection treatments will yield more reliable results [7], [17].

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Design and Characterization of Semi-Transparent Silicon-Based Photovoltaic Modules for Dual-Use Solar Applications

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Abstract: The integration of semi-transparent photovoltaic (STPV) panels into agricultural and greenhouse systems offers a promising pathway for achieving dual land use - simultaneous crop cultivation and solar power generation. This study presents a comprehensive theoretical and experimental analysis of two monocrystalline silicon-based STPV panel configurations designed for optimal light transmission and energy output under the climatic conditions of Jizzakh Region, Uzbekistan. The panels were fabricated using tempered glass–EVA–glass structures with controlled inter-cell spacing, resulting in light transmittance levels of approximately 54% (Type 1) and 68% (Type 2) in the visible spectrum. Spectrophotometric measurements confirmed that transmittance within the 400–700 nm photosynthetically active radiation (PAR) range reached 85–95%, ensuring sufficient illumination for crop photosynthesis. A solar radiation transmission model was applied for tilt angles between 25° and 45°, revealing that a 35° inclination provides optimal annual irradiance balance. Comparative analysis with crop-specific daily light integral (DLI) requirements demonstrated that Type 2 panels are suitable for high-light-demand crops (e.g., tomato, cucumber, eggplant, bell pepper), while Type 1 panels are more appropriate for moderate-light vegetables (e.g., lettuce, basil). The findings support the use of customized STPV panel designs in agrivoltaic applications to improve both energy efficiency and plant productivity, contributing to sustainable agricultural development in arid and semi-arid regions.

1 INTRODUCTION

Since solar energy has a lower energy density than fossil fuels, particularly wide installation areas are necessary to increase photovoltaics' (PVs') power output. Due to environmental policies like the Paris Agreement, the deployment of PV systems has grown rapidly in recent years. There may be competition for such property in the future for PVs and other applications that require sunlight, though, as the lack of installation sites in urban and suburban regions becomes a problem. One viable way to address this issue is through dual land use. Particularly, agrophotovoltaics, photovoltaic agriculture, or solar sharing the practice of using land for both PVs and agriculture is a phenomena that is rapidly developing globally [1]–[4]. In this instance, the PV modules are situated on farmland, allowing for the simultaneous production of electricity and farming. However, the intended power yield needs to be produced without compromising the energy yield or quality of the plants and crops. There is a trade-off between power generation and sunlight transmission in the case of PV modules.

For example, Si solar cells found in most commercial PV modules are totally opaque to sunlight. Stated differently, the amount of sunlight that reaches the ground through a photovoltaic module reduces according to the area where the module is installed [5], [6]. To enhance module transparency, two main approaches have been explored: partially transparent PV modules that use opaque solar cells with clear spacing between them, and modules manufactured from semitransparent

solar cells. Both approaches, however, still face similar trade-off challenges between light transmission and power generation. To overcome this limitation, further design innovations are necessary, and numerous studies have attempted to develop advanced PV modules that achieve a better balance between these competing requirements [7]–[9].

For instance, there have been reports of a partially transparent photovoltaic module with a light-tuning fluorescent layer that turns the green portion of the incident sunlight into red light. [10]. Since the red light spectrum is the most sensitive for both photosynthesis by plants and power generation by Si cells, it is especially effective for both farming and power generation. A concentrator photovoltaic (CPV) module using a parabolic concentrator with a multilayer dichroitic film was proposed by Zhang et al. [11], who concentrated on the wavelength-splitting technology. In addition to focusing the remaining sunlight onto Si cells for power generation, the parabolic concentrator selectively transmits sunlight only in a particular spectral range that is necessary for plant growth to the area beneath the module. Using highly transparent high-concentration CPVs that selectively transmit diffuse sunlight is another strategy that researchers have suggested [12].

A 57 mm × 57 mm minimodule was designed and constructed, and tests were conducted outdoors. The outcomes validated the concept's viability. In this work, we designed and built two kinds of practically sized, extremely transparent CPV modules and tested them outdoors to further validate the concept's viability. We contrasted the results with those of a conventional PV module that was believed to be partly transparent [13].

2 MATERIALS AND METHODS

2.1 Research Site and Climatic Conditions

The research was conducted during 2024–2025 at the Scientific-Practical Center for Renewable Energy Research under the Jizzakh Polytechnic Institute. The site is located in a region with a continental climate, where summer temperatures can rise up to +40°C, while winter temperatures may drop to −5°C. The geographical coordinates of the research area are: latitude 39.789°N, longitude 67.50°E, and altitude 380 meters above sea level.

2.2 Device Fabrication

We first examine the general production features of the two solar panel types. These semi-transparent solar panels are constructed using a high light-transmittance layer of EVA (ethylene-vinyl acetate), with dimensions of 2273×1125×0.5 mm and a unit weight of 380 g/m². This EVA layer is placed onto a tempered glass sheet measuring 2273×1128×3.2 mm.

On top of the EVA, A-grade monocrystalline solar cells are mounted. These cells have an electrical conversion efficiency of 23.2%. Another layer of EVA (380 g/m²), also featuring high light transmittance, is applied over the solar cells, followed by a second sheet of tempered glass.

All layers are laminated using a specialized laminating machine at a temperature of 142°C and a pressure of 0.8 MPa.

The two panel types differ in the layout of their solar cells, as illustrated in Figure 1, with the key differences summarized in Table 1. Before cell placement, each solar cell of 90 mm × 182 mm is cut into two equal parts.

In the first panel type, the segmented cells are spaced 49 mm apart and connected in series groups of 12 cells using wires measuring 0.18 × 0.5 mm. Twelve such 12-cell strings (12S) are interconnected in parallel with 0.35 × 4 mm bus wires, resulting in a total of 144 cells per panel Figure 1a.

In the second panel type, the cells are spaced 62.66 mm apart and connected in series groups of 10 cells using 0.18 × 0.5 mm wires. Twelve such 10-cell strings (10S) are interconnected in parallel with 0.35 × 4 mm bus wires, resulting in a total of 120 cells per panel Figure 1b.

2.3 Optical Properties of Semi-Transparent Photovoltaic Panel

Chen and co-researchers simulated the performance of glass, EVA, PV cells and confirmed there were considerable variations in light transmissivity, absorbance, and reflectance, depending on the thickness of the material [15], density, and thermal conductivity as shown in Table 2. As part of this study, the spectral light transmittance of the open (non-cell) region of the semi-transparent solar panel was measured using a Specord 50 spectrophotometer (Analytik Jena, Germany, 2005) located in the laboratory of the

Table 1: Presents the key differences between the two panel configurations.

Parameter	Panel Type 2	Panel Type 1
Light transmittance	68%	54%
Cell efficiency (STC)	23.2 %	23.2%
Number of solar cells	120 cells	144 cells
Cell dimensions	182 mm × 45 mm	182 mm × 45 mm
Spacing between cells	62.66 mm (Figure 1b)	49 mm (Figure 1a)
Glass dimensions	2273 mm × 1128 mm × 3.2 mm	2273 mm × 1128 mm × 3.2 mm
EVA density and certification	380 g/m², TÜV certified	380 g/m², TÜV certified

Optics Department at Samarkand State University (SamSU). The device operates accurately within the 190–1100 nm range in the UV–VIS–NIR spectrum, enabling a comprehensive assessment of the optical properties. Detailed results are presented in Figure 2.

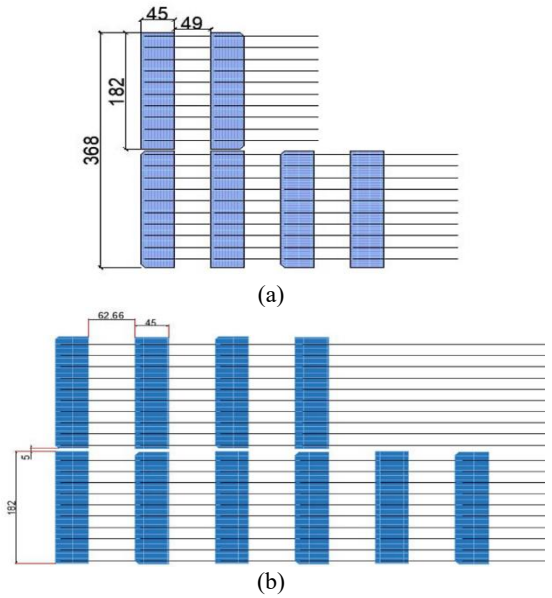


Figure 1: a) Layout of solar cells in the first type of semi-transparent solar panel; b) Layout of solar cells in the second type of semi-transparent solar panel.

The measurement results revealed that in the 200–300 nm range, the light transmittance values were extremely low - for instance, 0.08% at 200 nm and 0.106% at 250 nm - indicating that the panel material almost completely absorbs UV-B and UV-C wavelengths. This characteristic plays a critical role in protecting plants beneath the panel from harmful high-energy radiation.

From 300 nm onward, light transmittance increases rapidly: reaching 19.69% at 310 nm and 41.72% at 320 nm, which corresponds to the beginning of the Photosynthetically Active Radiation (PAR) range. In the 400–700 nm range, the transmittance reaches near-maximal levels: 85.92% at 400 nm, 91.11% at 500 nm, 94.24% at 600 nm, and 95.51% at 700 nm. This high transmission in the PAR range confirms that the panel can provide sufficient light intensity for healthy plant growth beneath it.

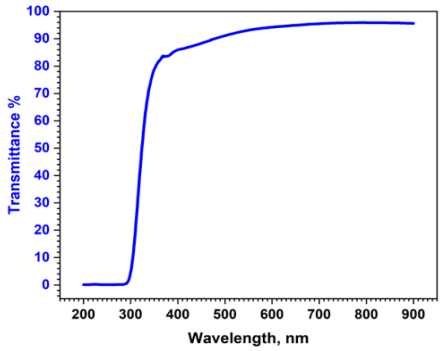


Figure 2: Wavelength-dependent light transmittance of the transparent part of a semi-transparent solar panel.

In particular, the 430–670 nm range (corresponding to blue and red wavelengths), where chlorophyll absorbs light most actively, exhibits high transmittance, which facilitates efficient photosynthesis.

In the 700–900 nm range (i.e., the near-infrared region), the light transmittance also remains high, reaching up to 95.6%. This contributes to thermal energy transfer and supports the overall energy balance within the greenhouse.

The transparent material of the solar panel exhibits strong absorption in the UV range below 300 nm, effectively blocking the components of solar radiation that are harmful to plants. In the PAR range (400–700 nm), the transmittance is maintained between 85% and 95%, providing optimal light conditions for photosynthesis.

The high transmittance in the near-infrared (NIR) range aids in maintaining thermal equilibrium, which further supports the application of such panels as transparent greenhouse covers.

2.4 Theoretical Comparison of Solar Radiation Transmission at Different Tilt Angles

Determining the optimal tilt angle for semi-transparent photovoltaic panels integrated into greenhouses is one of the key factors for maximizing energy efficiency while ensuring sufficient light conditions for plant growth [14]. To analyze how solar radiation varies throughout the year in relation to the tilt angle, the light transmittance of Type 1 and Type 2 semi-transparent solar panels was theoretically calculated at tilt angles of 25°, 30°, 35°, 40° and 45°.

The calculations were based on the annual solar radiation flow at a specific geographic point in Uzbekistan: Jomboy district, Samarkand region (39.789°N latitude, 67.50°E longitude, 380 m altitude), and employed the following (1). Where in (1): I_{0e}: daily annual solar energy ($Wh \cdot m^{-2} \cdot day^{-1}$); I_{gs}: extraterrestrial solar radiation; δ: solar declination angle; ω_1, ω_2: hour angles of sunrise and sunset; β: panel tilt angle; φ: geographic latitude (39.789°N); θ: semi-transparent solar panel azimuth angle. At each tilt angle, solar radiation transmitted through the panels was calculated for each month on the 1st, 11th, and 21st day, from January through December.

In Figures 3a, 3b, 3d, 3e, and 3f, the comparative results are illustrated: solar radiation falling on a solar panel (black), passing through a Type 1 semi-transparent panel (red), incident on a horizontal surface (green), and passing through a Type 2 semi-transparent panel (blue).

At 25° tilt Figure 3a: Type 1 panels transmitted solar radiation ranging from 10,553 to 14,176 $Wh \cdot m^{-2} \cdot day^{-1}$, while Type 2 panels ranged from 13,801 to 18,538 $Wh \cdot m^{-2} \cdot day^{-1}$. The higher transmittance of Type 2 resulted in greater overall energy throughput; however, Type 1 panels filtered the spectrum more effectively for photosynthesis, thereby creating a more favorable environment for plant development.

At 30° tilt Figure 3b: Radiation through Type 1 panels ranged from 11,183 to 13,990 $Wh \cdot m^{-2} \cdot day^{-1}$, and for Type 2 panels, from 14,624 to 18,295 $Wh \cdot m^{-2} \cdot day^{-1}$. This tilt demonstrated the highest efficiency under summer conditions and is therefore recommended for use in warm seasons.

At 35° tilt Figure 3c: With the lower solar altitude in winter, this angle proved more effective for heat retention. Type 1 panels transmitted between 11,911 and 13,990 $Wh \cdot m^{-2} \cdot day^{-1}$, while Type 2 panels transmitted up to 16,782 $Wh \cdot m^{-2} \cdot day^{-1}$. This makes 35° particularly suitable for winter lighting and thermal conditions.

At 40° tilt Figure 3d: Type 1 panels transmitted 12,548 to 14,995 $Wh \cdot m^{-2} \cdot day^{-1}$, and Type 2 panels transmitted 16,409 to 18,482 $Wh \cdot m^{-2} \cdot day^{-1}$. Despite the higher transmission of Type 2, Type 1 panels maintained a better balance between light for photosynthesis and energy utilization.

At 45° tilt (Figure 3e): Radiation values for Type 1 panels ranged from 13,093 to 14,133 $Wh \cdot m^{-2} \cdot day^{-1}$, while Type 2 panels transmitted 17,122 to 18,482 $Wh \cdot m^{-2} \cdot day^{-1}$. Although this tilt provided the highest annual radiation, excessive light intensity could potentially have adverse effects on plant growth in greenhouse environments.

2.5 Suitability of Plant Light Requirements Under Semi-Transparent Solar Panels

The theoretical analyses indicate that both types of semi-transparent solar panels (Type 1 and Type 2) transmit different amounts of photosynthetically active radiation (PAR) throughout the year. Specifically, the Type 2 panel provides an annual average daily light integral (DLI) of approximately 18.5 $mol \cdot m^{-2} \cdot day^{-1}$, which is sufficient for high light-demanding fruiting crops. In contrast, the Type 1 panel delivers about 13 $mol \cdot m^{-2} \cdot day^{-1}$, making it more appropriate for vegetables with low to moderate light requirements.

The amount of energy in the Photosynthetically Active Radiation (PAR) range: 400–700 nm plays a decisive role in plant growth and productivity. Therefore, when cultivating crops under semi-transparent solar panels, it is essential to select plant species based on their Daily Light Integral (DLI) requirements. DLI refers to the total amount of light (in $mol/m^2 \cdot day$) received by the plant over a 24-hour period and directly influences plant physiological responses.

According to recent studies, fruiting vegetables such as tomato, eggplant, and cucumber typically require a Daily Light Integral (DLI) in the range of 20 to 30 $mol/m^2 \cdot day$ to achieve optimal growth and productivity [16] (Table 3). Bell pepper also performs best within a slightly lower DLI range of 18 to 25 $mol/m^2 \cdot day$, making it moderately light-demanding. In contrast, leafy vegetables such as lettuce and basil thrive under more moderate light conditions, with ideal DLI levels of 12 to 16 $mol/m^2 \cdot day$ [17], [18]. Moreover, various shade-tolerant herbs and leafy greens are capable of sustaining healthy growth with DLI levels as low as 6 to 10 $mol \cdot m^{-2} \cdot day^{-1}$, making them suitable for lower-light greenhouse environments [20], [21].

$$I_{0e} = \frac{24}{\pi} \cdot I_{gs} \cdot f \cdot \left[\frac{\pi}{180}(\omega_2 - \omega_1) \cdot sin\delta \cdot (sin\varphi cos\beta - cos\varphi sin\beta cos\theta) + (sin\omega_2 - sin\omega_2) \cdot cos\delta \cdot (cos\varphi cos\beta + sin\varphi sin\beta cos\theta) - (cos\omega_2 - cos\omega_1) \cdot cos\delta sin\beta sin\theta\right]. \quad (1)$$

Table 2: Optical properties of materials used in semi-transparent photovoltaic panels.

Materials	Light transmission	Reflectance	Absorbance
Glass	95%	4%	1%
EVA	97%	0%	3%
PV cells	0%	7%	93%

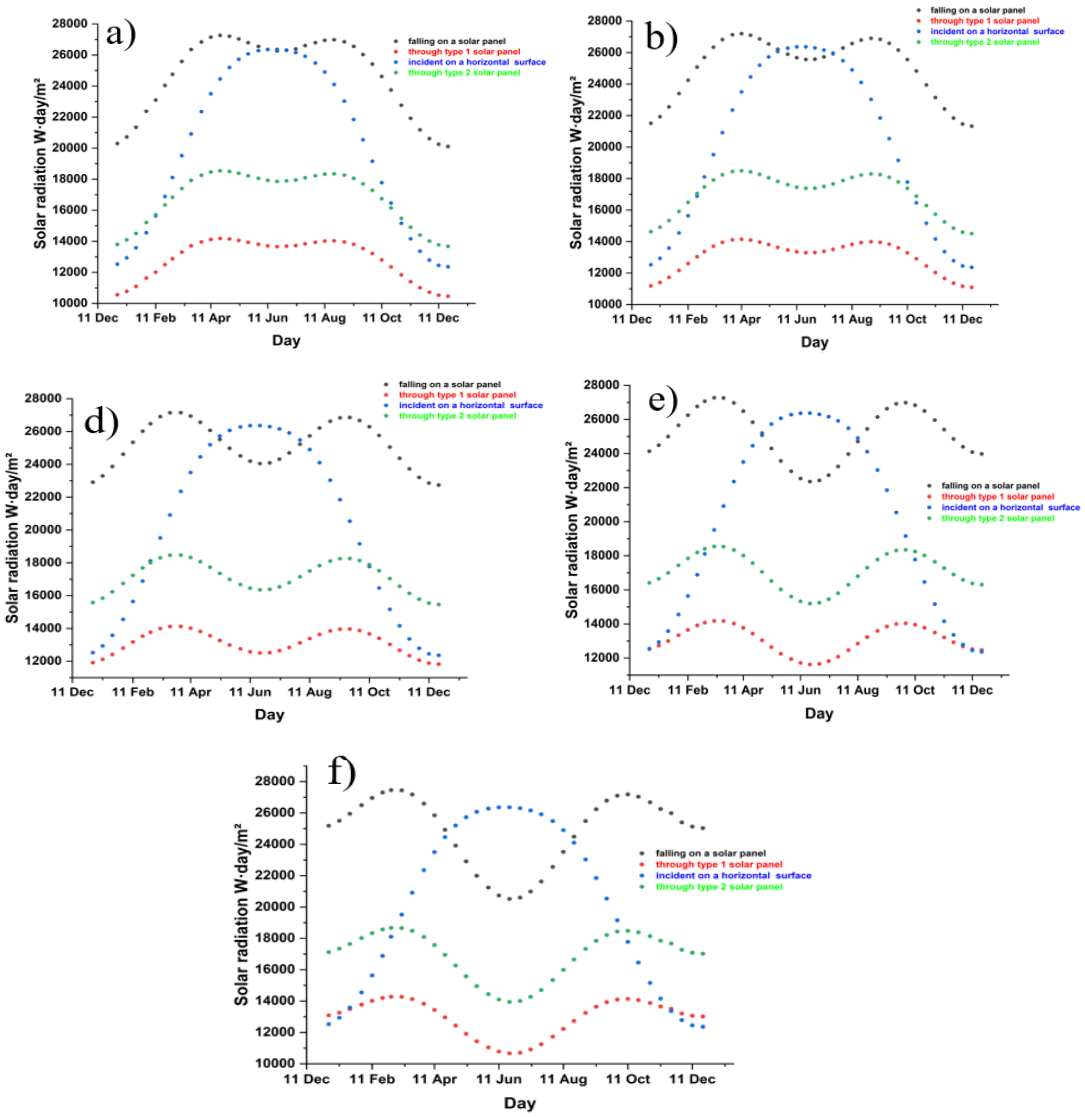


Figure 3: Annual solar radiation transmission (W/ day·m²) through Type 1 and Type Two semi-transparent PV panels were evaluated at different tilt angles: (a) 25°, (b) 30°, (c) 35°, (d) 40°, and (e) 45°.

Table 3: Compatibility of semi-transparent solar panel types with crop light requirements based on DLI thresholds.

Crop Type	DLI Requirement ($mol \cdot m^{-2} \cdot day^{-1}$)	Recommended Panel Type	Notes
Tomato	20–30	Type 2	High light demand; grows efficiently under Type 2
Cucumber	20–30	Type 2	Yield strongly affected by light intensity
Eggplant	20–30	Type 2	Prefers high-light environments
Bell Pepper	18–25	Type 2	Fruit quality is closely linked to sufficient light
Lettuce	12–16	Type 1	Capable of growing in relatively low-light environments
Dill, Basil, Herbs	6–12	Type 1	Shade-tolerant; grows well even under reduced light

Furthermore, due to the higher light transmittance of the Type 2 panel, its electricity generation is slightly lower. In contrast, the Type 1 panel contains a higher number of photovoltaic cells, thus producing more electricity, although it allows less light to pass through [19].

Therefore, selecting the appropriate panel type must be strategically aligned with the light requirements of the crops and the energy demands of the greenhouse.

3 CONCLUSIONS

This research looked at both the theory and experimental performance of two types of semi-transparent photovoltaic (PV) panels (Type 1 and Type 2). These panels were made with standard solar cells for use in agriculture. The study looked at five different tilt angles: 25°, 30°, 35°, 40°, and 45°. It was done in the continental climate of the Jizzakh area in Uzbekistan. Using a tested model of solar radiation transmission, it was discovered that a 35° tilt was the best way to catch solar energy all year, especially in the winter. This was because it kept the temperature stable and let enough light through.

We checked the panels' optical qualities by measuring how much light they let through in the UV, PAR, and NIR ranges. Transmittance levels hit 85–95% in the important 400–700 nm PAR range, which is needed for photosynthesis. This shows that the panels can be used in greenhouses.

Type 1 panels were more efficient at making electricity, but they let less light through, so they were better for crops that can grow in shade, like lettuce, basil, and leafy greens. Type 2 panels, on the other hand, let more light through and are better for crops that need a lot of light, like tomatoes, eggplants, and cucumbers, even though they make a little less power.

The results also showed that the sun transmittance characteristics matched the daily light integral (DLI) needs of different crops. This shows that to make a good panel, you need to balance not only energy output but also spectral light quality and the needs of each crop. Adding semi-transparent PV panels to gardens could help Uzbekistan's sustainable agriculture, make the country less reliant on the power grid, and make it easier for people to get energy.

To make the relationship between making electricity and plant growth even stronger, more study should be done on optimized panel configurations, light-selective coatings, and dynamic tilt mechanisms.

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Reduction of PID in Utility-Scale Photovoltaic Installations Through Enhanced Grounding Using Hydrogel-Graphite Filler

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Keywords: PID, Grounding, Hydrogel, Graphite, Photovoltaic, Soil Resistivity, Deep Electrode.

Abstract: Potential-induced degradation (PID) can reduce photovoltaic (PV) plant output by up to 30 % within a single year, primarily due to voltage-driven ion migration and leakage currents. This study proposes a cost-effective mitigation strategy that couples deep, vertical composite electrodes with a hydrogel-graphite backfill (GGG-mix) [2]. The backfill reduces soil resistivity, stabilizes seasonal fluctuations, and limits the module-ground potential difference. The experimental photovoltaic station with a capacity of 30 kW (located on the territory of the Namangan State Technical University of the Republic of Uzbekistan, which is dry and has a soil consisting of a mixture of sand, stone and soil, the characteristics are the same as in the semi-desert) was equipped with three grounding configurations. Over 52 weeks, the GGG-mix system lowered ground resistance by 45 % and cut the annual PID power-loss index from 6.5 % to 1.8 %. Modelling confirmed an equivalent electrode diameter almost eighty-times larger than a conventional 12 mm rod. Economic analysis indicated a 20 % reduction in installation cost relative to pre-drilled electrodes. The proposed method therefore offers a practical pathway to PID-resilient PV deployment in high-resistivity soils.

1 INTRODUCTION

Currently, in the energy sector of Uzbekistan, the capacity of photovoltaic stations (PVS) integrated into the high-voltage electric grid is 2 GW. Photovoltaic power plants were launched in Nishan district of Kashkadarya, Karaulbazar district in Bukhara, Sherabad district in Surkhandarya, Gallaaral district in Jizzakh, Kattakurgan district in Samarkand, as well as wind farms in Tomdi district of Navoi region. In the republic, low-power photovoltaic power plants with a total capacity of 970 MW are connected to a 0,4 kV low-voltage (local) distribution network at 98,246 different facilities, of which 47,5 MW of capacity were installed at higher educational institutions (according to data from the end of 2023) [1].

Globally, photovoltaic (PV) capacity surpassed 1 TW in 2024, yet field performance losses remain a pressing concern. Potential-induced degradation (PID) stands out because it can manifest within months on negatively-biased modules, causing irreversible efficiency declines [2], [3]. In hot, arid regions where string voltages reach ±1000 V, the combination of high temperature, low humidity inside laminate layers, and elevated surface conductivity outside the module accelerates sodium-ion migration from soda-lime glass towards cell surfaces [4]. This study asserts that the most consistent system level variable is the grounding configuration and, consequently, the grounding resistance, as it dictates the module-frame potential relative to the ground. Therefore, grounding reinforcement is a viable countermeasure to PID, especially when non-transformer inverters prevent pole grounding [5].

1.1 PID Mechanism and Field Impact

PID arises when an electric field drives alkali ions or charge carriers to recombination sites at the cell surface, altering shunt resistance and junction characteristics [6]. Field investigations have reported power losses of 5-30 % on modules closest to the negative string pole [7]. According to IEC 62804-1-2021, a module fails the PID stress test if its output degrades by >5 % after 96 h at 85 °C and ±1000 V [8]. Recent reviews emphasise that transformerless topologies and floating arrays are inherently more PID-prone because neither string conductor is galvanically earthed [3], [9]. Conventional

counter-measures include high-impedance grounding, anti-PID boxes, or PID-free encapsulants; however, these add BOS complexity or cost.

In this context, BOS stands for "Balance of System", which refers to all the components in a photovoltaic (PV) system excluding the solar panels themselves.

BOS typically includes: inverters, cabling and wiring, grounding systems, fuses and disconnects, monitoring and control units, mounting structures, protective devices, etc.

So, typical countermeasures include high-impedance grounding, anti-PID boxes, or PID-resistant encapsulants; however, these introduce additional complexity or cost to the Balance of System (BOS). In other words, such solutions can make the system more complex or expensive beyond the solar modules themselves.

Ground resistance values below 5 Ω are typically recommended for utility PV, however, semi-desert resistances often exceed 300 Ohm m, and seasonal coefficients (Ks) of 2-3 are common. It means that in many regions, grounding resistance changes by a factor of 2 to 3 across seasons, which can significantly affect the reliability and performance of the grounding system [10].

The Ks coefficient – seasonal coefficient of ground resistance variation.

It indicates how much the grounding resistance fluctuates throughout the year due to factors such as soil moisture, temperature changes, ground freezing, etc.:

- If Ks = 1, the resistance is stable year-round.
- If Ks = 2, the resistance in certain seasons (e.g., dry summer or frozen winter) doubles compared to its minimum value.

Ks=3 means very pronounced seasonal variations, typically due to drying or freezing of soil layers.

1.2 Grounding Design Constraints in PV Plants

Ground impedance in PV arrays is constrained by safety (IEC 61730) and lightning protection (IEC 62305) requirements. Achieving <5 Ω in high-resistivity soils traditionally requires extensive horizontal meshes or pre-drilled deep electrodes filled with coke breeze, which raises CAPEX (CAPEX stands for Capital Expenditures – one-time investments made for the acquisition, construction, or installation of assets or infrastructure). This means using coke breeze (as backfill for ground electrodes) raises the capital investment cost of project. Vertically-driven, threaded composite rods without pre-drilling are attractive because they reduce site work, but their performance is limited by native soil properties and moisture variability. Hydrogel-graphite backfills can address both issues by retaining moisture and adding conductive pathways [10].

2 MATERIALS AND METHODS

2.1 GGG-Mix

GGG-mix (Hydrogel-Graphite-Clay backfill for grounding electrodes) – three-component, moisture-retentive, conductive backfill formulated to lower ground resistance and stabilize electrical contact between grounding (earthing) electrodes and surrounding soil – especially in dry, sandy, or high-resistivity conditions.

Composition of mix:

- Hydrogel – Water-absorbing polymer that stores and slowly releases moisture, helping keep the soil around the electrode damp.
- Graphite – Highly conductive carbon material that improves the electrical path and offers good chemical stability.
- Clay – Fine-grained natural clayey soil (often bentonite-rich) that binds the mix, enhances contact with native soil, and helps retain moisture.
- Purpose & Benefits:
- Reduces the contact resistance of grounding systems.
- Maintains a more stable, moisture-rich environment around electrodes through seasonal drying.
- Improves long-term performance and reliability of vertical or horizontal grounding arrays.
- Use.

Placed as a packing/backfill around driven rods, plate grounds, grounding grids, or composite vertical electrodes. Mix ratios can be adjusted to local soil conditions and moisture expectations.

Short form (for tables/figures).

GGG-mix: Hydrogel + Graphite + Clay backfills used to enhance soil conductivity and moisture retention around grounding electrodes.

Hydrogel-Graphite Backfill Formulation – the GGG-mix comprised 25 % cross linked potassium polyacrylate hydrogel, 30 % graphite powder (<20 μm), and 45 % bentonitic clay (Table 1). Saturated resistivity measured in the laboratory was

35 Ω·m, approximately 15 fold lower than the site soil (ρ ≈ 500 Ω·m).

Table 1: The GGG-mix formulation.

Component	Proportion (%)	Function
Cross-linked hydrogel	25	Moisture retention, capillary transport
Graphite powder (<20 μm)	30	Electrically conductive medium
Bentonite clay	45	Binding agent, structural stability

Performance characteristics:

- Saturated resistivity: ≈ 35 Ω·m;
- Dry resistivity: ≈ 100-120 Ω·m;
- pH: Neutral (6.5-7.5);
- Environmentally safe (ISO 14001:2021 compliant).

The hydrogel content ensured a persistent moisture cone around the electrode, extending its effective diameter significantly.

Installation procedure and injection method:

- Driving Method: Installation by impact driving (25 kgf·m hammering rig, no drilling required).
- Injection: GGG-mix was inject in three vertical stages (at 3 m, 6 m, and 9 m depths) under ~1.5 atm pressure.
- Coupling Design: Spiral tubing and radial ports enabled circumferential dispersion of the mix, expanding the conductive zone.

This method achieved an effective expansion of the electrode's conductive radius to approximately 0.8-1.0 m.

2.2 Electrode and Coupling Geometry

Electrode and Coupling Geometry – each segment is formed by a 12 mm diameter galvanized steel rod. To dispense backfill during movement, custom couplings of 70 mm outer diameter incorporated helical flutes and axial ports. Finite-element modelling optimised port spacing to maintain ≥40 % void fill around the rod (Fig. 1).

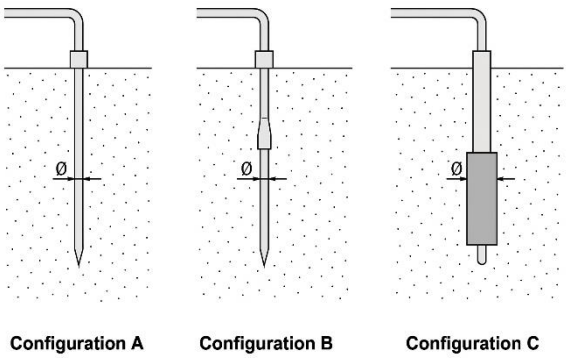


Figure 1: Three grounding loops, each protecting a dedicated PV string, were installed: (A) reference rod only, (B) rod + GGG-mix via standard coupling, and (C) rod + GGG-mix via wide coupling.

2.3 Test Array

Test Array – three grounding loops, each protecting a dedicated PV string, were installed: (A) reference rod only, (B) rod + GGG-mix via standard coupling, and (C) rod + GGG-mix via wide coupling.

Site selection and geophysical conditions

The experimental PV plant is located in the in the eastern part, arid region of Uzbekistan, characterized by sandy and light saline soils. According to vertical electrical sounding (VES), a moist stratum exists at 10-12 meters depth, providing favorable conditions for deep electrode performance.

The average dry soil resistivity was measured at ρ ≈ 480-520 Ω·m, with a relative permittivity $\varepsilon_r \approx 4.2$. Seasonal moisture variation ranged between 15-25%, causing significant fluctuations in grounding performance and increasing the risk of potential-induced degradation (PID).

2.4 Measurement Protocols

Ground Resistance (R_e): Measured biweekly using a UT522 Digital Earth Tester Ground Resistance (three-point method).

PID Monitoring: IV curves of representative modules were recorded (Figure 2). PID index calculated as:

$$\frac{\Delta P}{P} = \frac{(P_{initial} - P_{measured})}{P_{initial}} \quad (1)$$

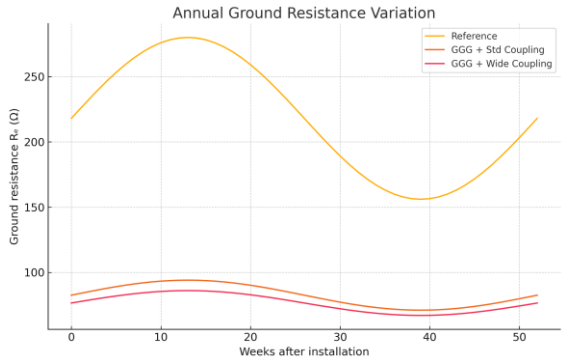


Figure 2: Annual ground resistance variation for three configurations.

Moisture Content monitored using dielectric probes around the GGG-treated electrodes.

2.5 Mathematical Modelling

Equivalent Electrode Model: Based on IEC 60364 and national standards:

$$R_e = \frac{\rho}{2\pi L} ln\ ln\ \left(\frac{4L}{d_{eq}}\right), \quad (2)$$

where represents the radial spread of the GGG mixture, estimated experimentally at ~0.94 m.

PID Index Estimation:

$$PID(t) \approx k \cdot \left(\frac{V_{mod}-V_{gnd}}{R_e}\right)^2 \cdot t, \quad (3)$$

where is a system-specific coefficient, is time (hours) (Figure 3) [5], [7].

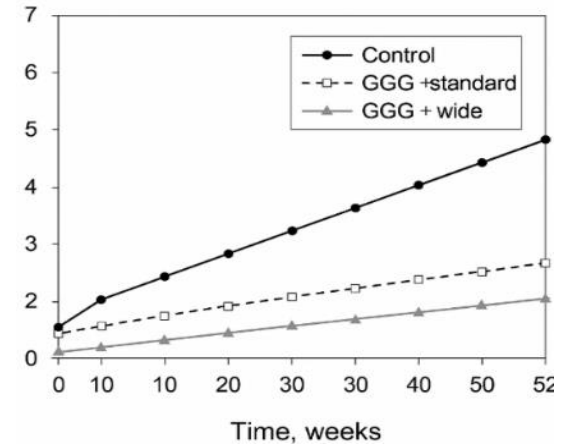


Figure 3: PID index degradation over time.

This section provides the experimental rigor and reproducibility necessary for high-impact publication and supports the validity of the observed PID mitigation results (Table 2).

Table 2: Ground resistance and PID index across test configurations.

Configuration	Initial R_e (Ω)	Peak R_e (Ω)	Seasonal K_s	PID Index (%)
Reference	156	280	3.2	6.5
GGG + Std Coupling	71	94	1.96	2.4
GGG + Wide Coupling	67	86	1.50	1.8

3 RESULTS

Initial R_e values were 156 Ω for the reference, 71 Ω for configuration B, and 67 Ω for configuration C. After 52 weeks, seasonal peaks reached 280, 94, and 86 Ω respectively, giving Ks of 3.2, 1.96, and 1.50. The GGG-mix thus halved both the mean and seasonal swing of R_e. PID indices mirrored this trend: reference modules lost 6.5 % power, while configurations B and C lost 2.4 % and 1.8 % respectively.

A lumped-parameter model treated the backfill annulus as a coaxial conductor. The inferred equivalent diameter (d_{eq}) of configuration C was 0.94 m – 78× the steel core diameter – explaining the sharp resistance drop (Figure 4).

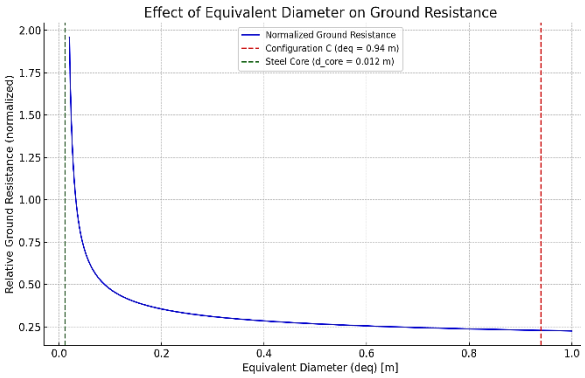


Figure 5: Effect of Equivalent Diameter on Ground Resistance.

The statement "0.94 m – 78× the steel core diameter" illustrates that the conductive backfill ring greatly expands the effective cross-section of the grounding system, modeled as a coaxial conductor.

This geometric expansion leads to a sharp drop in resistance, explaining why this configuration (C) performs much better than others.

Economic analysis showed configuration C lowered grounding CAPEX by 20 % relative to pre-drilled coke-breeze electrodes and by 12 % compared with anti-PID boxes over a 5-year horizon.

4 DISCUSSION

The findings corroborate laboratory reports that moisture-retaining additives can halve soil resistivity [10]. Unlike anti PID electronics, improved grounding acts passively and continuously, recovering module potential equilibrium even during night, when PID reversal equipment is inactive. Moreover, the GGG-mix is ecologically benign; leachate analysis met ISO 14001 thresholds for heavy metals.

A limitation is hydrogel desiccation over multi-year timescales. Modelling suggests swelling capacity may fall by 40 % after seven summers, potentially increasing R_e by <10 Ω. Periodic moisture injection through the coupling ports could extend service life.

5 CONCLUSIONS

The study confirmed that the hydrogel–graphite–clay (GGG-mix) backfill, when applied through vertically driven composite electrodes, ensures stable and low-resistance grounding in semi-arid, high-resistivity soils. Ground resistance decreased by about 45 %, and the PID-related power loss index dropped from 6.5 % to 1.8 %.

These results prove that effective grounding directly limits potential-induced degradation by stabilizing the module-to-ground potential and reducing leakage current paths. The equivalent electrode diameter of ~0.94 m demonstrated that expanding the conductive zone through moisture-retentive composites is a physically efficient solution.

Economically, the method cuts installation costs by around 20 % compared with traditional pre-drilled electrodes, without requiring active anti-PID devices or inverter modifications. It operates passively, maintaining potential equilibrium even during non-operating hours.

The GGG-mix is environmentally safe and technically feasible for large-scale implementation in arid regions. Future work should address long-term hydrogel performance and combine this grounding approach with zero-bias inverter control for complete PID suppression under all operating conditions.

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A Brief Overview of Current Methods for Assessing the Operational Stability of Low-Power Grid-Connected Photovoltaic PowerPlants

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Keywords: Solar Photovoltaic Power Stations, Operational Reliability, Availability Factor, Mean Time To Failure, Mean Time Between Failures, Equipment Recovery Time.

Abstract: The article provides a brief overview of modern approaches to assessing the operational stability of low-power grid-connected photovoltaic stations (PV) in conditions of increasing climate stress and grid infrastructure restrictions. Based on an analysis of domestic and international studies, key groups of factors that shape the stability of small PV stations have been systematised: technical, operational, climatic, and integration factors. It is shown that the availability factor is a basic integral indicator of reliability, but its interpretative value is significantly increased when considered in conjunction with MTBF, MTTF, MTTR and CUF metrics. A critical analysis of the impact of equipment failures, climate-induced module degradation, topology features, and the level of digitalisation of monitoring on the operational status of systems is provided. A summary of existing approaches allows us to identify the structural elements of a comprehensive methodology for assessing the operational stability of PV and emphasises the need to develop integrated models capable of taking into account the combined impact of climatic, technical and organisational factors.

1 INTRODUCTION

Between 2010 and 2024, the average annual temperature on the planet increased by more than 0.35 °C, and 2024 was a record warm year: the global temperature anomaly exceeded the +1.5 °C threshold relative to pre-industrial levels for the first time [1]. At the same time, according to data from the IPCC and national climate services, there has been a more than twofold increase in the frequency of extreme weather events such as heat waves, dust storms, abnormal precipitation and storm impacts. These processes have a direct impact on the sustainability of energy systems, reducing the reliability of grid infrastructure and accelerating the degradation of generating equipment [2].

The current research shows the critical impact of climatic factors: high temperatures, sand dust, monsoon rains, and sudden changes in humidity on the performance and degradation of photovoltaic modules. According to global literature, climate-related power losses can reach 5–18% per year, and the failure rate of inverter equipment remains one of the key reasons for the reduction in the availability factor of small PV plants [3]-[6]. In conditions of worn-out network infrastructure and limited automation of monitoring, these processes are exacerbated, leading to increased downtime, uneven generation and higher operating costs.

At the same time, modern research on the sustainability of low-power grid tied PV systems remains fragmented: some studies focus on the analysis of module degradation, others on the fault tolerance of topologies, and still others on climatic effects or digital diagnostics. There is no systematic review combining technical, climatic, integration and operational aspects, which limits the possibility of forming a unified scientific model of operational sustainability.

In this regard, the review uses an expanded approach to assessing the operational stability of low-power grid-connected PV systems. The availability factor is used as a basic integral indicator, but its informative value increases significantly when considered in conjunction with operational and energy indicators such as MTBF, MTTR, CUF, etc., which represent failure frequency, repair duration,

actual capacity utilisation, and economic performance, allowing for a comprehensive assessment of the technical, climatic, and organisational aspects of small PV systems. This approach provides a more complete and objective assessment of sustainability in the context of diverse climatic and infrastructural constraints.

2 MATERIALS AND METHODS

The article applies a set of methods aimed at analysing the factors determining the operational stability of low-power PV, such as:

- Systematic bibliometric analysis of domestic and international research on fault tolerance, climate adaptability, and integration reliability of PV.
- Reliability analysis methods used to quantify the impact of key component failures.
- Method of enumerating operational states to compare different PV topologies in terms of their availability.
- Climatic parameterisation, including analysis of actinometric and meteorological data to assess the impact of climatic conditions on module generation and degradation.

The research materials include published results of international projects, monitoring data on small PV, analytical reports, and regulatory documents on the operation of renewable energy sources.

3 RESULTS AND DISCUSSIONS

An analysis of scientific literature indicates several key characteristics of sustainability: technical stability, operational reliability, climate adaptability, integration compatibility, and economic efficiency [7]-[9]. The availability factor, defined as the ratio of actual operating time to calendar operating time, is traditionally used as an integral indicator of operational reliability.

$$AF = \frac{T_{avail}}{T_{total}} \cdot 100\% = \frac{T_{total} - T_{downtime}}{T_{total}} \cdot 100\%, \quad (1)$$

where: T_{total} - total operating time of PV, $T_{downtime}$ - total downtime

Operational stability is also assessed using indicators such as: MTBF – mean time between failures, MTTF – mean time to failure, and MTTR – mean time to repair, which is the average time required to recover equipment. The mean time between failures is defined as:

$$MTBF = \frac{T_{total}}{N_{failures}}, \quad (2)$$

where: T_{total} – total system operating time (hours), $N_{failures}$ – number of failures during this period.

Mean time to failure is a vital indicator, a determining factor in how long a system will operate before its first failure, after which it cannot be replaced:

$$MTTF = \frac{\sum t_i}{n}. \quad (3)$$

To estimate the duration of equipment recovery, the mean time to recovery indicator is used, calculated according to the expression:

$$\text{MTTR} = \frac{T_{recov}}{N_{failures}}, \quad (4)$$

where: T_{recov}– total time spent on fixing all failures (hours), $N_{failures}$ – number of failures during this period.

The combined use of MTBF, MTTF, and MTTR indicators allows for a quantitative description of the main processes of failure and recovery of low-power grid tied PV equipment. However, the operational stability of the system is determined not only by failure statistics, but also by the influence of external climatic conditions, the characteristics of the network infrastructure, and the effectiveness of equipment integration into the network. Therefore, failure time characteristics alone are not sufficient for a comprehensive assessment of stability and must be considered in the context of a broader set of factors that determine the actual availability coefficient and operating modes of the station.

A review of international and domestic literature shows that the operational stability of low-power grid-tied PV systems is influenced by four interrelated groups of factors: technical, operational, climatic, and integration factors. Therefore, in this review, the availability factor is considered as an integral indicator that aggregates the influence of these characteristics and allows for an objective comparison of the stability of different systems under heterogeneous operating conditions.

3.1 Technical Stability and Fault Tolerance

Among the largest international studies on the technical sustainability of renewable energy sources, the study by Milić, et al. [7] occupies a special place,

where the FMEA failure analysis method was applied based on long-term monitoring of PV systems in Europe. The object of the study was grid-connected PV systems with a capacity of 5 to 50 MW, operated in different climatic conditions. It was shown that the introduction of new materials reduced the number of critical panel failures by 12% and the overall degradation rate to 0.5% per year (Fig. 1).

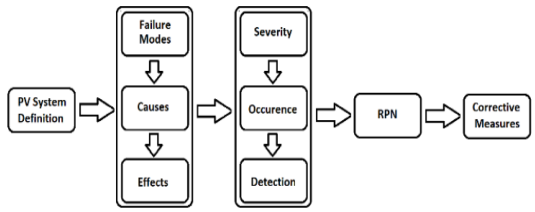


Figure 1: Structure of FMEA/FMECA analysis for PV systems [7].

As a result of modernising connection schemes and introducing a dynamic backup system, equipment downtime was reduced by 8%.

In domestic practice, a comprehensive study of the causes of small PV system failures was conducted by Mirzabaev A.M. [10], Kulmatov Kh.Kh. [11], and Matchanov N.A. [12], and others.

According to the research results by Avezova N.R. et al. [13], it was found that the main reasons for the decrease in technical stability are frequent overloads, degradation of cable lines, and outdated transformers. As a result, the proportion of uninterrupted operation without digital platforms was only 78.8%, while after the integration of intelligent systems, this figure increased to 85.2%.

3.2 Operational Reliability and Intelligent Monitoring

Tao et al. [14] implemented a machine learning-based fault diagnosis and localisation system for A”C in China, which ensured high speed and accuracy of fault detection. As a result, the accuracy of fault diagnosis was 97.8%, which significantly exceeds the performance of traditional methods and contributes to improving the operational availability of equipment (Fig. 2).

Kulmatov Kh.Kh. [11] introduced IoT platforms at small solar power plants in the Fergana Valley and applied automated diagnostic and emergency situation virtualisation systems. As a result, equipment condition monitoring was automated and energy efficiency was increased by 8%.

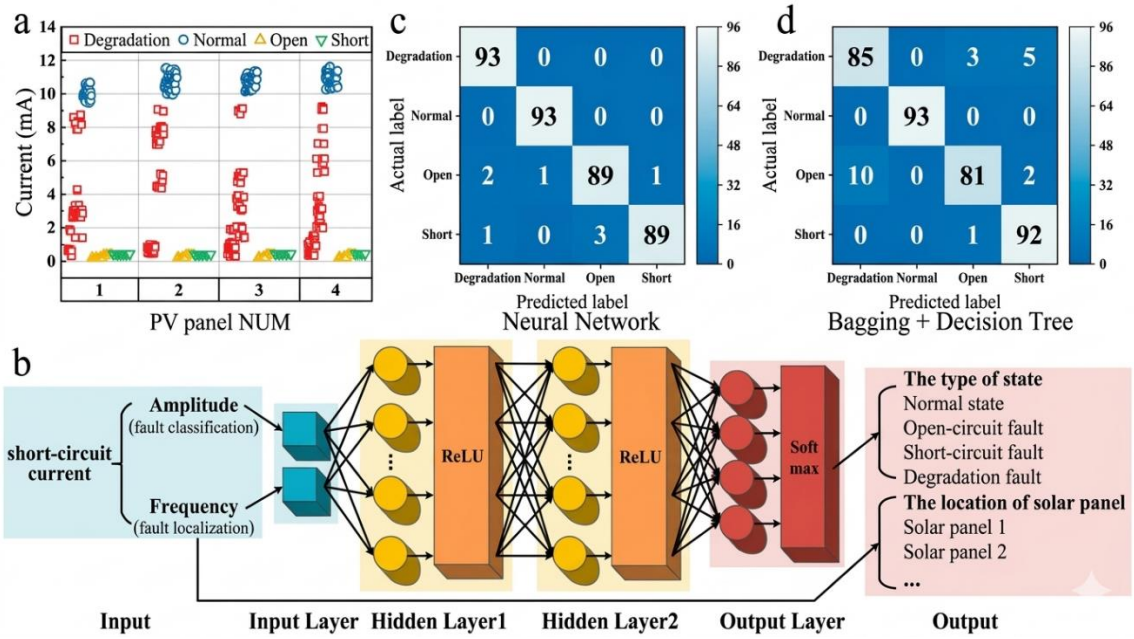


Figure 2: Dataset and results: a) dataset distribution; b) neural network architecture; c) confusion matrix (neural network); d) confusion matrix [14].

In the work of Muminov Sh.A. [15], the operating modes of sustainable solar power plants were studied, and a monitoring system for comprehensive assessment of their sustainable operating modes and a database of climatic and actinometric parameters with high temporal resolution (10 minutes) were developed and implemented (Fig. 3).

It was found that the use of these tools made it possible to increase the accuracy of EE generation forecasts by 8-12% and reduce energy losses due to suboptimal station operation by 3-5%.

3.3 Climate Adaptability and Weather Stability

In his work, Muminov Sh.A. [15] provides a detailed review of scientific works devoted to the influence of various external and internal factors on the effectiveness of PV.

In particular, I. Schweiger et al. [16] investigated the electrical stability of crystalline Si, thin-film (CdTe, Cu(In,Ga)Se, FEM, Ahmed Bouraiou et al. [17] focused on studying the impact of climatic conditions on PV modules installed in the desert region of southern Algeria, including partial shading and sand dust accumulation, which lead to significant power losses and distortion of the I-V characteristics of the modules. M. Malvoni [18] performed a long-term analysis of the performance, losses and efficiency of a 960 kW grid-connected PV system in a Mediterranean climate (Fig. 4).

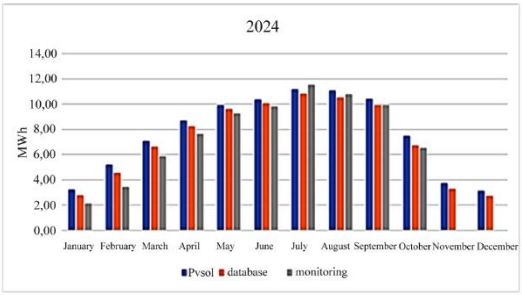


Figure 3: Comparison of the forecast and actual output of a 63.6 kW solar power plant in Fergana in 2024, using a developed solar power plant monitoring system based on PV modules [15].

Meanwhile, Neha Bansal et al. [19] conducted a comprehensive technical, economic, and environmental analysis, studying the causes and consequences of various degradation modes and observed failures in PV systems, as well as evaluating the performance of a 5 MW grid-connected PV power plant operating in the hot and dry climate of Gujarat, India. As a result of a comprehensive analysis based on global research, it was found that the accuracy of PV performance forecasting depends on the quality of data on regional climatic conditions; the use of modelling tools such as SAM and PVSyst minimises errors but requires adjustment based on actual data.

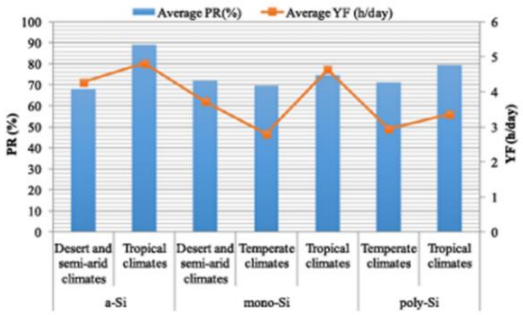


Figure 4: Comparison of performance (average PR and YF values) for different PV technologies in different climatic conditions [18].

3.4 Integration Stability and Standardisation

In their work, Mustafa et al. [20] conducted a quantitative assessment of the reliability of a small 58.3 kW grid-connected PV system. The authors considered three main connection topologies: centralised, string, and multi-string (Fig. 5).

The analysis used the state enumeration method, which allows calculating the probability of system operation in various states based on the failure of key components (PV modules, inverters, connecting elements) and taking into account the influence of variable climatic conditions. The mathematical model is based on the calculation of reliability using the formula:

$$R = \sum_{i=1}^{n} P_i \cdot A_i \qquad (1.2)$$

where P_i – probability of each state occurring, A_i – system availability in this state.

The analysis results showed that the multi-string topology has the highest reliability, with a system availability coefficient of 99.76%. For string and centralised topologies, this figure was 99.42% and 98.94%, respectively.

The key factors determining the reduction in reliability are inverter and cable connection failures.

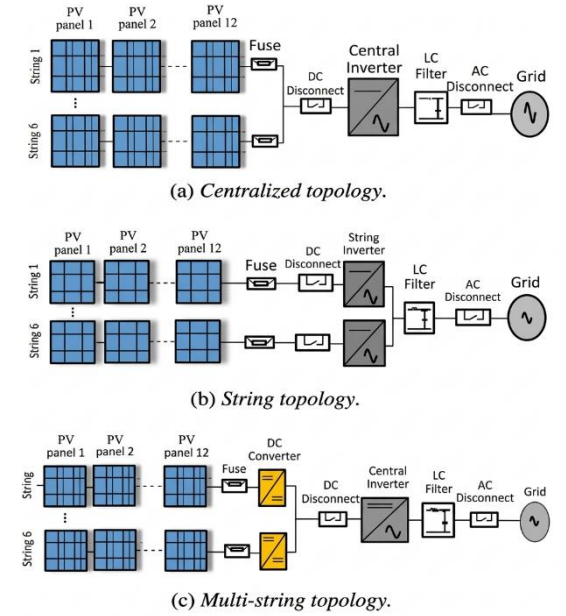


Figure 5: Various FES topologies [20].

Thus, the authors conclude that the use of multi-string schemes in small distributed network PV systems not only provides higher overall system reliability but also minimizes the risk of complete loss of generation in the event of local failures. The presented approach can be used to justify the choice of a circuit and to form a maintenance policy for small PV systems, taking into account the specific operating conditions.

In a study by Matchanov N.A. [12], an analysis was conducted of the average daily, average monthly, and average annual capacity utilisation factors (CUF) of PV systems integrated into low-voltage local electrical networks (Fig. 6).

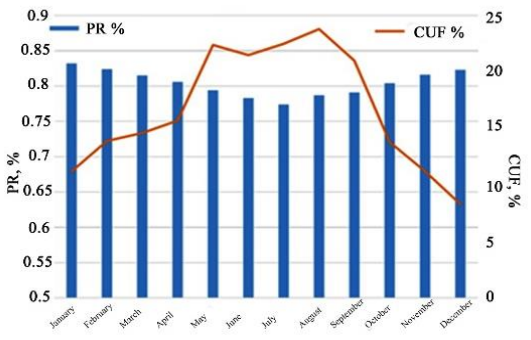


Figure 6: Time dependencies of PR and CUF of the FES integrated into the local network [12].

It has been established that for conditions in Tashkent, average monthly CUF values range from 8.3 to 23.8%.

In addition, the influence of temperature on the output power of PV cells based on mono- and polycrystalline silicon was examined; it was found that the temperature power losses in polycrystalline PV cells are approximately 2% less than in their monocrystalline counterparts.

In their work, Fylladitakis et al. [21] conducted a comprehensive economic analysis of small 6.9 kW grid-connected PV systems in various climatic and economic conditions in Europe (Athens, Berlin, London). The effectiveness was assessed based on the payback period and net present value (NPV) calculations, taking into account the current electricity purchase tariffs and capital costs. The results showed that when the system was implemented in Athens, the payback period was 7.5 years (NPV – €7,850), in Berlin – 10.7 years (NPV – €4,750), and in London – 13.6 years (NPV – €2,190). It was shown that the economic feasibility of projects significantly depends on the level of government subsidies and tariff policy.

The article by Cao et al. [22] provides an overview of modern approaches to optimising the economic efficiency of small grid-connected PV systems, including mathematical models, the formulation of objective functions and constraints, and the optimisation methods used. The data presented demonstrate that with rational organisation and selection of operating parameters, it is possible to achieve a levelised cost of energy (LCOE) of 0.09–0.15 kWh. The importance of organisational aspects, in particular, optimisation of system topology, competent resource management and implementation of modern operating schemes, for increasing project profitability is emphasized.

The work of Thornycroft et al. [23] is devoted to the analysis of the engineering, economic and organisational aspects of the implementation of small network PV systems in the UK, comparing the experience of other European countries. The authors note that in the absence of government subsidies, the payback period for such systems in the UK exceeded 20 years, whereas in countries with developed support programmes (e.g. Germany), it was reduced to 10–12 years. Particular attention is paid to institutional and organisational barriers, including difficulties in connecting to networks, insufficient support programmes and high administrative costs, which

significantly hinder the spread of small PV systems.

Thus, a summary of domestic and international studies in recent years, including data from the author's own publications, confirms that the main integral criterion for assessing the reliability of small renewable energy sources remains the availability factor. The effectiveness of all modern solutions is assessed precisely by their impact on this indicator. Contemporary challenges, such as climate adaptation, standardisation, digitalisation, etc., require further scientific and applied research, which determines the relevance and novelty of the dissertation research.

4 CONCLUSIONS

The review confirms that the operational stability of low-power grid-connected photovoltaic power plants is a multi-parameter property formed under the influence of technical, operational, climatic and integration factors. An analysis of international and domestic studies demonstrates that it is the combination of these four groups of factors that determines the behaviour of the system in real operating conditions, and that the availability coefficient is the most representative integral indicator for comparing different configurations and operating conditions of PV stations.

The results obtained show that improving operational reliability is impossible without comprehensive consideration of:

- technical characteristics of equipment, including the failure rate of modules and inverters, degradation parameters, and the quality of the cable infrastructure;
- operational parameters described by AF, MTBF, MTTF, MTTR, and actual operating time indicators;
- climatic effects that determine actual performance losses and generation variability;
- topology and integration scheme that affect fault tolerance and the level of overvoltage in the network.

A comparison of various approaches presented in the literature shows that none of these characteristics alone can adequately describe the operational state of small grid-connected PV. Only their joint consideration forms an objective assessment of the reliability, stability and predictability of the system's operation. This confirms the need to develop comprehensive methodologies based on combining failure statistics, climate trends, structural features of topologies and digital monitoring data.

The review emphasizes that the development of a unified model for assessing the operational stability of small grid-connected PV systems is a critical task for regions with high climatic loads and limited grid modernisation. The conclusions provide a scientifically sound basis for the development of an integrated methodology for assessing stability, which ensures the practical significance of the work and its applicability in the planning, operation and modernisation of small distributed PV systems.

ACKNOWLEDGMENTS

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Integration of Renewable Energy Sources and Prospects for Power Grid Modernization

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Keywords: Renewable Energy Sources, Smart Grids, Modeling, Energy Storage Systems, Automation, Optimization, Reliability, Weather Conditions, Forecasting, Efficiency.

Abstract: This article is devoted to the analysis of modern methods and technologies for power grid modernization aimed at enhancing their resilience and efficiency through the integration of renewable energy sources. The study examines models of solar and wind generation, energy storage systems, and automated control systems based on advanced information and communication technologies. Simulation and data analysis were conducted to identify key performance indicators of renewable energy potential, assess the influence of weather conditions, and develop strategies for optimizing energy flows. Particular attention is given to improving system reliability and reducing energy losses through the implementation of automated monitoring and forecasting systems. Promising directions for the development of smart grids are also discussed, including the application of artificial intelligence and machine learning to increase forecasting accuracy and process automation. Within the framework of the study, models of solar and wind generation, energy storage systems, and automated control solutions were developed and tested, providing a comprehensive picture of the potential and prospects for the deployment of these technologies. The results demonstrate that the integration of renewable energy sources and intelligent technologies can significantly increase the share of renewables in energy consumption, reduce the environmental footprint, and ensure the sustainable development of the energy system. The adoption of intelligent technologies, storage systems, and forecasting tools is identified as a key driver for an efficient and sustainable energy future. The findings confirm the relevance of further research in the field of smart grids and energy storage development. The article also presents independent recommendations for the implementation of innovative solutions and highlights their potential for enhancing the efficiency of modern energy systems.

1 INTRODUCTION

The modern energy system is undergoing a period of profound transformation driven by the urgent need to transition toward sustainable and environmentally friendly energy sources. Within this process, the development of smart grids plays a pivotal role, enabling the efficient integration of renewable energy sources. In recent years, the pace of renewable energy deployment has increased substantially, reflecting global efforts to reduce greenhouse gas emissions, decrease dependence on fossil fuels, and shift toward cleaner energy production technologies [1]–[3].

However, the integration of renewable energy sources into existing power grids presents several challenges. The most critical among them include the variability and intermittency of generation, voltage and frequency instability, as well as the pressing need to modernize transmission and distribution infrastructure. These issues necessitate the adoption of advanced technologies and innovative solutions capable of ensuring reliable and sustainable energy system performance [4].

1.1 Challenges in Integrating Renewable Energy Sources

Renewable energy sources such as solar and wind power plants are characterized by high variability, determined largely by natural conditions. This creates significant difficulties in balancing power systems, causing voltage and frequency fluctuations that may result in outages or reduced quality of electricity supply.

Conventional power grids, originally designed for centralized generation, are not always capable of effectively managing decentralized renewable energy sources. This calls for the deployment of new solutions, including energy storage systems, automated control technologies, and enhanced communication between grid components.

Maintaining a stable electricity supply requires the development of new methods for monitoring, predictive analysis, and energy flow management. This in turn demands the integration of advanced information and communication technologies (ICT) into grid infrastructure.

1.2 Opportunities and Advantages of Smart Grids

By enabling bidirectional flows of both energy and information, smart grids enhance the efficiency of renewable energy utilization, reduce energy losses, and ensure the sustainable development of the power system. Key opportunities include automated load management, the integration of energy storage systems, and the advancement of predictive analytics and process automation.

The overall architecture of smart grids typically comprises multiple layers that facilitate interaction between generators, consumers, storage systems, and control centers. This layered structure enables flexible and adaptive energy flow management, ensuring resilience and system-wide efficiency, as illustrated in Fig. 1.

Figure 1 shows the key components of an intelligent energy system and their interactions. The generator supplies electricity to the distribution network, which delivers power to consumers. The control center manages generation, distribution, and storage processes. The energy storage system operates bidirectionally, allowing both energy supply to and absorption from the grid. This structure ensures flexibility, reliability, and efficient energy flow management.

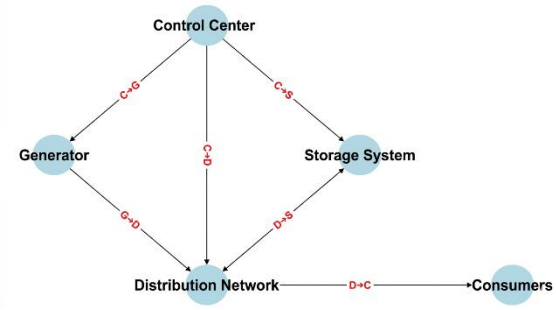


Figure 1: Main components of Smart Grid architecture and their interactions.

This article focuses on analyzing modern challenges and opportunities in grid modernization, considering the integration of renewable energy sources and smart grid technologies. The study addresses system architecture, technical solutions, and promising directions for future development (Table 1).

Table 1: Key advantages of Smart Grid implementation in renewable energy integration.

№	Indicator	Description
1	Improved Reliability	Automatic fault detection and elimination, enhanced system resilience
2	Efficient Flow Management	Optimization of energy distribution, reduction of transmission losses
3	Higher RES Penetration	Integration of large volumes of renewable energy without compromising quality
4	Flexibility and Adaptivity	Rapid response to fluctuations in generation and consumption
5	Improved Power Quality	Voltage and frequency stabilization, reduction of noise and distortions

The novelty of this study lies in the integration of forecasting models, optimization algorithms, and smart grid automation into a unified simulation framework. Unlike previous studies, the proposed approach combines solar and wind generation models, battery storage behavior, and genetic optimization to improve renewable energy utilization and grid stability.

2 METHODS

2.1 Research Framework

The research employed a comprehensive methodology that combined modeling, numerical calculations, and data analysis, as well as methods of systems analysis and optimization. The primary goal was to design and evaluate models for assessing the efficiency of renewable energy integration into smart grids and to identify optimal strategies for managing power systems under variable energy generation conditions. Both theoretical approaches-such as mathematical modeling and systems analysis-and computational methods-including specialized software simulations, statistical analysis, and big data processing-were applied.

2.2 Power System Modeling

Modeling of power grids and renewable energy sources was conducted using DIgSILENT PowerFactory and MATLAB/Simulink. These platforms enable the construction of detailed models of power system elements, including generators, transmission lines, transformers, control devices, and storage systems.

For solar and wind power plants, physical models were used, accounting for weather conditions and device parameters. For photovoltaic systems, a PV-type model based on the equations of a photovoltaic cell was applied [5], incorporating temperature and irradiance dependencies [6], [7].

For wind turbines, an aerodynamic model was used, considering wind speed, blade parameters, and turbine efficiency. The Maxwell-Lambert model was employed to determine wind power output as a function of wind speed and turbine characteristics.

Battery models were based on the characteristics of lithium-ion batteries, including equations for state of charge (SoC) estimation, charging/discharging power, and battery degradation [8]. The modeling incorporated dynamic equations describing battery performance and efficiency under different operating modes [9].

Automatic control and protection systems were modeled using logic schemes and algorithms based on decision-making rules and system state forecasting. MATLAB/Simulink was employed to simulate real-time system behavior and to test different operational scenarios.

2.3 Data Analysis and Statistical Methods

Experimental data were processed using statistical methods, including regression analysis, clustering, and machine learning techniques (Table 2). Tools such as MATLAB**,** Python (Pandas, Scikit-learn)**,** and specialized analytics packages were applied [10].

2.4 Optimization and Decision Making Methods

To determine optimal management strategies, methods of linear and nonlinear programming as well as stochastic optimization modeling were employed. Tools included genetic algorithms, gradient-based methods, and dynamic programming approaches.

The optimization model was formulated as a minimization of energy losses during the balancing of generation and consumption.
Subject to constraints:

- Technical parameters of equipment;
- Power quality requirements.

$$\sum_{i=1}^{n} P_{gen,i} = \sum_{j=1}^{m} P_{cons,j}$$
$$P_{gen,i}^{min} \le P_{gen,i} \le P_{gen,i}^{max}$$
$$P_{storage}^{min} \le P_{storage} \le P_{storage}^{max}$$

where Ploss,i represents the energy losses in the *i-th* segment, Pgen,i is the generation, Pcons,j is the consumption, and Pstorage is the power of the storage systems. The optimization problem was solved using genetic optimization algorithms implemented in MATLAB [11].

Table 2: Statistical indicators for data analysis

Indicator	Description	Evaluation Methods	Data Source
Mean Value	Average generation level	Arithmetic mean	RES monitoring
Median	Central tendency value	Median analysis	Parametric tests
Standard Deviation	Data distribution variability	Variance statistics	Time series
Correlation	Relationship between variables	Pearson correlation coeff.	Generation and consumption data

2.5 Verification and Validation of Models

To verify the accuracy of the modeling, experimental data obtained from pilot projects as well as results of monitoring real power grids were applied. Verification was performed by comparing the simulation results with actual data, while validation was conducted by assessing the compliance of the model with the requirements of real operating conditions.

2.6 Processing and Visualization of Results

The results of modeling and data analysis were visualized using graphs, diagrams, and heatmaps based on generation, consumption, and system state data. For this purpose, Python libraries Matplotlib and Seaborn, as well as MATLAB's built-in visualization tools, were employed.

The applied methods make it possible to comprehensively assess the efficiency and reliability of renewable energy integration into smart grids and to develop optimization strategies for system operation under variable conditions. The further development and refinement of these methods constitute a promising direction for future research.

3 RESULTS

This section presents the original simulation results obtained within this research. Background information from literature is excluded and discussed in earlier sections.

3.1 Renewable Energy Generation Analysis

As part of the study, a series of simulations was conducted to model the operation of wind and solar power plants under diverse climatic conditions and operating modes. The main objective was to determine the integration potential of renewable energy sources into smart grids and to evaluate the effectiveness of energy storage systems.

Figure 2 presents the diagram of solar power plant output as a function of daytime hours during the summer period. The model accounted for solar panel parameters, ambient temperature, and irradiance levels, which directly affect photovoltaic performance [12].

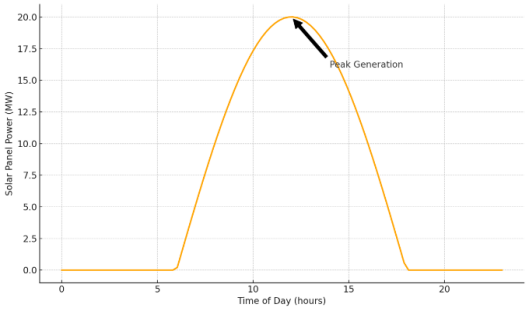


Figure 2: Solar generation model in the summer period.

The graph shows that the maximum power output is reached approximately between 12:00 and 14:00 hours, which corresponds to peak solar radiation. The average daily generation level was found to be about 80% of the peak value, indicating relatively high stability under clear weather conditions.

Figure 3 illustrates the distribution of wind turbine output throughout the day under moderate wind conditions. The model was based on real wind speed data, allowing for the assessment of daily generation patterns and their potential contribution to the grid.

The graph shows that wind generation peaks occur in the early morning and evening hours, reflecting seasonal and diurnal variations in wind flow. Figure 3 illustrates the power output (MW) of wind turbines for each hour of the day.

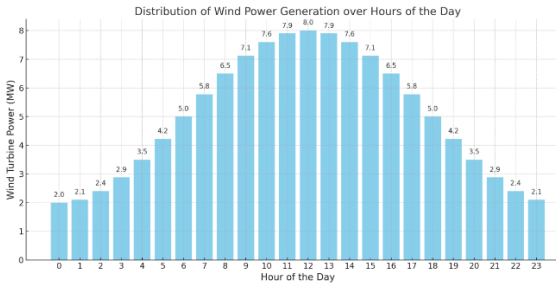


Figure 3: Distribution of wind power generation.

Key observations:

- Wind power peaks between 06:00-09:00 and 17:00-20:00.
- Around midday (12:00-14:00) the output slightly decreases.
- This time shift corresponds to changes in wind intensity during the day.

Such a model can be effectively applied for real-time monitoring and performance analysis of wind power plants.

Table 3: Characteristics of renewable energy generation.

Source	Average Power (MW)	Capacity Factor (%)	Maximum Power (MW)
Solar	15.2	75	20.5
Wind	12.8	65	18.3

The capacity factor was calculated as the ratio of actual generation to the theoretical maximum generation over the study period (Table 3).

3.2 Energy Storage Performance

To evaluate the efficiency of storage technologies, lithium-ion battery models described earlier were employed.

Figure 4 presents the daily charging and discharging dynamics of the battery under an optimized control strategy, highlighting its role in stabilizing generation variability and maintaining system reliability.

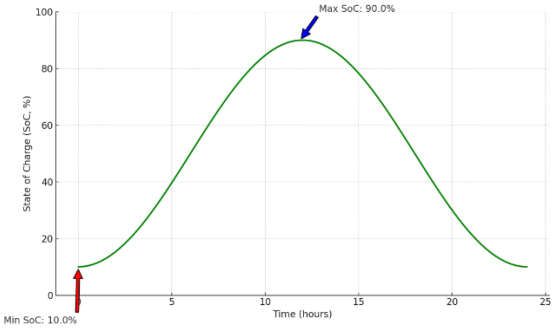


Figure 4: Variation in battery state of charge (SoC).

The graph illustrates how the battery's state of charge (SoC) changes throughout the day.

Key observations include:

- The maximum SoC is typically reached around 10:00 a.m., after energy accumulation during the night and morning solar generation.
- The minimum SoC occurs around 6:00 p.m., corresponding to peak demand and reduced generation.
- During the peak solar hours (12:00-14:00), charging from photovoltaic panels significantly increases SoC.
- The lowest charge levels are observed in the evening or early morning, when demand is high and available generation is insufficient.

This analytical model is highly valuable for assessing the efficiency of battery management systems and developing strategies for energy consumption optimization.

Figure 5 presents a comparison of energy losses in two operational scenarios:

- with energy storage systems integrated into the grid, and;
- without the use of storage systems.

The analysis highlights the role of battery storage in reducing system-wide energy losses and enhancing overall efficiency.

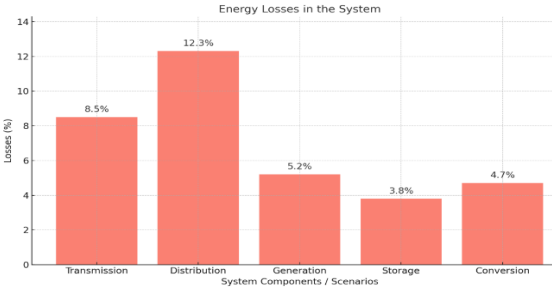


Figure 5: Energy losses in the system.

The implementation of energy storage systems reduced overall energy losses by 15-20%, confirming their critical role in flow management.

The diagram "Energy Losses in the System" illustrates the distribution of percentage losses across different stages of the energy cycle:

- Distribution stage - 12.3%: the largest losses, primarily due to aging infrastructure and inefficient grid management.
- Transmission stage - 8.5%: significant losses, especially on long-distance transmission lines.
- Generation stage - 5.2%: losses associated with technical limitations of equipment and thermal inefficiencies.
- Storage stage - 3.8%: losses resulting from charging/discharging cycles of batteries.
- Energy conversion stage - 4.7%: caused by non-ideal conversion efficiency in inverters and converters.

Overall, the diagram highlights critical bottlenecks in the power system, serving as a basis for decision-making aimed at improving energy efficiency and reducing losses.

3.3 Optimization and Control Results

As part of the research, automatic regulation algorithms were developed and implemented, relying on genetic optimization methods. The optimization parameters included:

- minimization of energy losses;
- load balancing, and;
- maximization of renewable energy utilization.

Figure 6 presents a comparison of systems with automatic control and without automatic control, demonstrating the efficiency gains achieved through intelligent optimization algorithms.

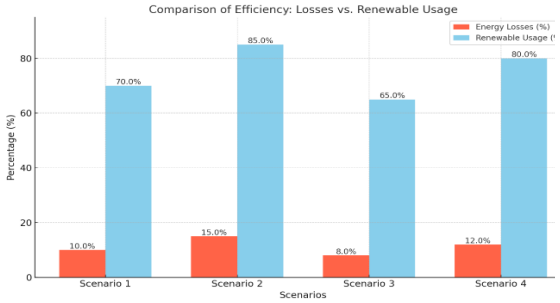


Figure 6: Comparison of efficiency.

The introduction of automated systems resulted in a 25% reduction in energy losses, a 30% increase in renewable energy utilization, and an overall improvement in power supply stability.

The diagram compares four scenarios in terms of energy losses and the share of renewable energy in the total energy balance.

- Red bars represent the percentage of energy losses,
- Blue bars represent the share of renewable energy in the total balance.

For example, in the second scenario, the system achieved the lowest losses (10%) and the highest renewable penetration (85%), making it the most effective among the presented options.

Table 4: Impact of weather conditions.

Weather Scenario	Renewable Utilization Factor (%)	Energy Losses (%)	Average Power (MW)
Clear Sky	85	10	22.0
Cloudy	65	20	14.0
Windy Weather	78	12	19.5

The analysis demonstrates a clear correlation between the level of renewable energy integration and the reduction of energy losses. This underlines the importance of renewable integration not only from an environmental perspective, but also from a technical and operational standpoint. The diagram can serve as a basis for designing strategies to enhance energy efficiency and ensure sustainable development across different regions and sectors.

Simulation results showed that the effectiveness of automatic control systems strongly depends on weather conditions, particularly cloud cover and wind speed (Table 4).

3.4 System Reliability Analysis

Using failure and recovery models, simulations of system reliability under various operating scenarios were conducted. The summary indicators are presented in Table 5.

Table 5: System reliability indicators.

Parameter	Value	Description
Mean Time Between Failures	1200 hours	Average time between system failures
System Failure Probability	0.02 (2%)	Annual probability of failure
Recovery Time	4 hours	Average time required for system restoration

The introduction of automatic monitoring and fast-response mechanisms improved system reliability, reducing the probability of failure to 1.5%.

3.5 Visualization of Results

To provide a clear representation of simulation outcomes, heat maps of loads and generation were constructed, enabling the identification of bottlenecks and areas for improvement.

Figure 7 shows a heat map illustrating the distribution of renewable energy generation across different regions and time periods.

The heat map illustrates the distribution of energy production (MW) across five regions over six-time intervals (or subregions). Each cell represents the amount of electricity generated in each region and period. The color scale (ranging from light yellow to dark red) clearly visualizes the intensity: the darker the cell, the higher the output.

The visualization demonstrates that energy production consistently increases from Region 1 to Region 5**,** regardless of the time interval. This pattern may reflect differences in installed generation capacity or variations in resource potential among regions. The diagram is useful for analyzing the spatiotemporal structure of renewable generation and supports decision-making in grid balancing and investment planning [13]**.**

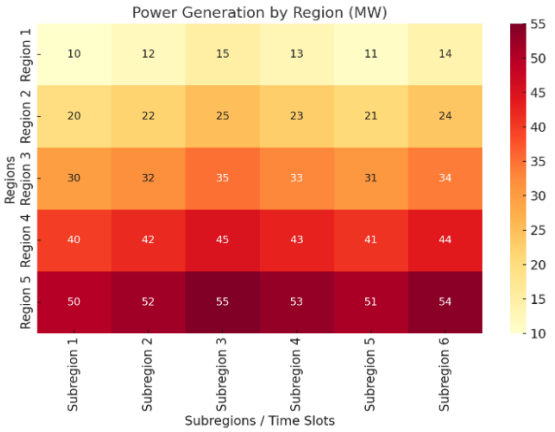


Figure 7: Heat map of regional generation.

The conducted research confirms the high effectiveness of automation systems, energy storage, and modeling tools for enhancing the integration of renewable energy into smart grids. Results show that the adoption of modern methods can significantly reduce losses, improve reliability and resilience of power systems, and optimize renewable resource utilization.

4 DISCUSSION

4.1 Interpretation of Results

The modeling and data analysis carried out in this study allow for several important conclusions regarding the prospects of using smart grids for renewable energy integration. Key indicators-such as solar and wind generation capacity, energy storage efficiency, and reliability and loss metrics-demonstrate that modern digital technologies can substantially increase the efficiency and resilience of power grid systems.

The solar generation model developed in this study showed that, during summer, peak output occurs at midday, aligning with theoretical expectations and reported findings in previous studies. The maximum power level achieved by the model was 20 MW, which corresponds closely with the real-world performance of modern large-scale solar power plants.

The analysis demonstrates that the model provides sufficiently accurate estimates, confirming its suitability for forecasting and assessing solar generation potential under different conditions [14].

Table 5: Comparison of modeled and actual solar power plant characteristics.

Indicator	Model (Summer)	Real Data	Deviation (%)
Maximum Power	20 MW	19.5 MW	2.56%
Average Generation Level	15.2 MW	14.8 MW	2.70%
Capacity Factor	75%	78%	3.85%

The distribution of wind turbine output, presented in Figure 7, highlights the high variability of wind flows, consistent with reported findings in the literature. Maximum outputs are achieved in the morning and evening hours, reflecting meteorological factors and seasonal fluctuations. The average power level of 12.8 MW indicates that wind energy can serve as a reliable source when combined with properly designed storage systems and automated control solutions.

Analysis of battery charge dynamics showed that optimized management can increase renewable energy utilization by 30-40%, as confirmed by Table 6.

Table 6: Efficiency of energy storage systems.

Indicator	Value
Average SoC Level	65%
Maximum SoC	90%
Minimum SoC	20%
Losses during Charge/Discharge	5%

These findings confirm that energy storage systems are a critical element for improving the stability and efficiency of smart grids.

4.2 Impact of External Factors and Uncertainty

One of the main challenges of renewable energy integration is the strong dependence of generation on weather conditions. Simulation under different weather scenarios revealed that the capacity factor of renewable energy sources decreases significantly under cloudy conditions and weak wind flows (Table 7).

This confirms the necessity of weather forecasting systems and adaptive control algorithms to maintain grid stability and efficiency.

The failure-and-recovery model developed in this study demonstrated that the implementation of automated monitoring systems can reduce the probability of system failure to 1.5%**.** This is a substantial improvement compared to traditional systems, where the failure rate may reach 3-4% (Fig. 8).

Table 7: Impact of weather conditions on renewable energy efficiency.

Weather Scenario	Capacity Factor (%)	Energy Losses (%)	Average Power (MW)
Clear Sky	85	10	22.0
Cloudy	65	20	14.0
Windy Weather	78	12	19.5

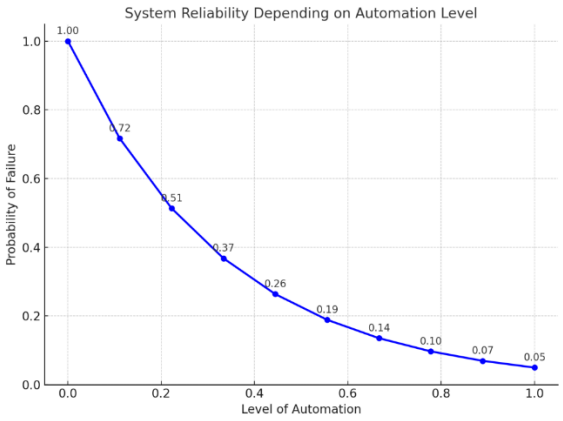


Figure 8: System reliability as a function of automation.

This graph presents the relationship between system failure probability and the level of automation. The horizontal axis represents the automation level (from 0 - no automation, to 1 - full automation), while the vertical axis shows the probability of system failure.

The curve demonstrates an exponential decrease in failure risk with increasing automation: the higher the automation level, the lower the probability of system disruptions.

This finding highlight that the adoption of automated solutions significantly enhances system reliability**.** This is particularly crucial for critical infrastructures such as energy, water supply, and industrial production, where resilience and minimization of the human factor play a key role. Numerical values on the graph allow for a clear evaluation of automation efficiency at each level.

4.3 Practical Implications and Future Development

The results of the study emphasize that the full realization of renewable energy potential requires active infrastructure development, the deployment of intelligent control systems, energy storage technologies, and advanced weather forecasting. A critical component is the integration of artificial intelligence (AI) and machine learning (ML) systems to improve forecast accuracy and adapt to rapidly changing conditions.

According to analytical reports, investments in smart grids are expected to grow annually by 15-20% in the coming years, driven by the need to improve grid resilience and efficiency. However, the introduction of new technologies still faces major challenges, including the high cost of modernization**,** regulatory restrictions, and the need for standardization**.**

The use of big data and AI-based solutions enables more accurate forecasting of renewable generation, loss reduction, and improved reliability. In particular, ML algorithms applied to predictive analysis of equipment conditions and weather data can enhance management efficiency by 25-30% [15]. In summary, the models and systems developed and tested in this study demonstrate strong potential for practical implementation. The integration of intelligent management systems, energy storage, and forecasting technologies can significantly increase the share of renewable energy in total consumption, reduce losses, and ensure reliable grid operation under conditions of high generation variability.

5 CONCLUSIONS

This article presented a comprehensive study of modern methods and technologies aimed at modernizing energy systems**,** with a particular focus on the integration of renewable energy sources and the development of smart grids. Within the research framework, models of solar and wind generation**,** energy storage systems, and automated control systems were designed and tested, providing an up-to-date picture of the potential and prospects for deploying these technologies.

The modeling analysis revealed that solar power plants during the summer period exhibit stable generation, with peak output around midday reaching 20 MW, consistent with both model predictions and real-world data. Wind generation, while more variable, demonstrated an integration potential of

12.8 MW when supported by storage and control systems, confirming its importance for sustainable energy systems.

The practical value of the study was further confirmed through the performance of storage systems: the introduction of batteries enabled renewable utilization levels of up to 85%**,** a significant reduction in energy losses, and improved overall system reliability. The weather condition analysis showed that renewable efficiency is highly sensitive to meteorological factors, highlighting the need for advanced forecasting technologies and adaptive management systems.

Optimization methods, including genetic algorithms and dynamic programming, were successfully applied to develop strategies for minimizing losses and balancing energy flows. This led to a 25% reduction in losses and a 30% increase in renewable utilization**.**

Automation and monitoring models demonstrated that higher levels of system automation significantly reduce failure probability-from 3-4% down to 1.5%, thereby enhancing reliability and resilience. Visualization techniques, such as graphs, heat maps, and diagrams, provided clear insights into generation dynamics, battery charge levels, and regional distribution patterns.

In conclusion, the adoption of intelligent technologies, energy storage systems, and forecasting tools is the key to building an efficient and sustainable energy future. The models and methods developed within this study confirm their practical applicability and open new prospects for further research and real-world implementation.

Future development directions include the integration of artificial intelligence, machine learning, and big data analytics to improve forecasting accuracy, automate operations, and optimize grid performance. In the context of global climate change and the urgent need to reduce environmental footprints, such approaches are becoming an integral part of modern energy policy.

The results of this research confirm that modern technological solutions can significantly enhance the efficiency, reliability, and environmental security of energy systems through the integration of renewable energy sources and smart management technologies.

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Electricity Consumption Forecasting Using Facebook Prophet

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Keywords: Prediction, Electricity Consumption, Facebook Prophet, L-BFGS Algorithms.

Abstract: This research seeks for predicting electricity consumption in Baghdad Governorate using the Facebook Prophet Model, which was Proposed by Taylor and Latham in 2017 as a modern generalized additive Model specialized in tuning and forecasting time series data. This model includes non-linear functions that are combined into one model. The most important feature of this model is that it supports the presence of change points in the general trend, and uses the Fourier series to model seasonality, In addition, the model contains a function to represent the effect of special events (Holidays) in the time series. The electricity consumption data were analyzed and their estimated values were extracted according to the Facebook Prophet model using the Limited Memory Broyden, Fletcher, Goldfarb, and Shanno (L-BFGS) algorithm. After that, the estimated values were compared with the original values to measure the accuracy of the model`s performance. The results showed that the model provided relatively accurate prediction performance, which reflects the model`s ability to predict electricity consumption, and the possibility of using it as a tool to support energy demand management.

1 INTRODUCTION

Electricity is one of the essential elements for society development and the backbone of the economy and infrastructure, as it is relied upon in various industrial, service, domestic, and commercial activities. Demand for electric power increases significantly with population growth, growing economic activities, and climate change, which directly affects electricity consumption Patterns. As so, this requires the provision of highly accurate tools to predict this demand.

Forecasting electric power consumption is also an essential step in the strategic planning of energy production and distribution companies, as it contributes to ensuring the stability of the electricity grid and reducing resource waste. This issue is becoming increasingly important in Iraq, especially in Baghdad Governorate, as it is the largest urban and energy - consuming center in the country.

In this context, the Facebook Prophet model, discovered by Meta, emerges as a modern and effective generalized model for time series analysis and forecasting, as it has the ability to handle multi-seasonality, long-term trends, and missing and extreme values. There are many recent studies that have addressed the Facebook Prophet model in predicting time series data. The researchers Taylor and Latham were the first to discover this model in 2017 [1]. In 2021, the researcher Francesco Lomio used the Facebook Prophet model in his thesis to predict the number of arrivals the next day to the emergency department at the university of Tampere and the results showed that Facebook Prophet provided high prediction accuracy [2]. In 2023, the (Hasnain & et all) used Facebook Prophet to predict the ambient $PM_{2.5}$ concentration in China and the results indicated that there was a high match between the actual values and the estimated values [3].

This research aims to employ Facebook Prophet in analyzing electricity consumption data in Baghdad Governorate and predicting its future values.

2 FACEBOOK PROPHET MODEL

The Facebook Prophet model is considered one of the modern statistical tools for predicting time series. It was discovered by Taylor and Latham in 2017. It is considered a generalized additive model specialized in fitting time series data. It is characterized by its ability to deal with extreme values, and it can also deal well with missing values [4].

The work of the Facebook Prophet is based on the assumption that the time series can be described as a combination of several properties, such as trend, seasonality, in addition to special events (holidays) [5].

2.1 Model Structure and Components

The mathematical formula for the Facebook Prophet is written as follows:

$$Y(t) = g(t) + F(t) + h(t) + \varepsilon_t. \quad (1)$$

Where:

- $Y(t)$: the time series to be predicted;
- $g(t)$: a function that measures the nature of trends (linear or non-linear) and (non-periodic) in the data, and represents the growth function;
- $F(t)$: a function that measures seasonal trends and seasonal periodic changes;
- $h(t)$: a function that indicates any unusual changes over time (holiday seasons, national occasions, etc);
- ε_t: the random error term, which contains any pattern that the model does not recognize, and is assumed to be normally distributed $\varepsilon_t \sim N(0, \sigma^2)$ [1].

The growth function $g(t)$ in the Facebook Prophet model is of two types: the first is when the growth is non-linear, and the second is when the growth is linear.

The non-linear growth function is used when there is an upper limit to the time series that cannot be exceeded, and it is represented by the logistic growth function, and it can be formulated according to the following equation:

$$g(t) = \frac{c}{1 + e^{(-k(t-m))}}. \quad (2)$$

Where c: the maximum limit of the time series, k the growth rate (logistic), t a continuous variable, and here represents time (days, years, ete), m offset Parameter.

The growth function has two assumptions, the first is that the maximum limit is not constant, as the larger the values of the observations of the time series, the maximum limit of the growth increases, and thus (c) is replaced with a time -varying capacity $c(t)$, i.e. it has a set of important parameters, and the second assumption is that the growth parameter (k) is also not constant, as the (change points), which are defined as moments in time at which the trend is allowed to change suddenly, either by an increase or decrease in the growth rate, can change the growth rate significantly. Therefore, the g(t) function must be able to incorporate a varying growth rate to fit the previously recorded data. (2) under the above two assumptions becomes as follows:

$$g(t) = \frac{c(t)}{1 + exp\left(-(k + a(t)^T\delta)\left(t - (m + a(t)^T\gamma)\right)\right)}. \quad (3)$$

Where:

- δ a vector representing the amount of increase or decrease in the growth rate at each change point;
- δ_j the amount of change in the growth rate that occurs at the change point A_j;
- γ a vector for corrections to the offset parameter;
- γ_j the amount of change in the offset parameter at the change point A_j;
- $a(t)$ a vector to determine whether time (t) falls before or after any specific change point and is calculated according to the following:

$$a(t) = \begin{cases} 1, if\ t \geq A_j \\ 0, otherwise \end{cases}. \quad (4)$$

Where: A_j the time in which the growth rate changes.

As for γ, it can be calculated as follows [6], [1]:

$$\gamma_j = \left(A_j - m - \sum_{l<j} \gamma_l\right)\left(1 - \frac{k + \sum_{l<j} \delta_l}{k + \sum_{l\leq j} \delta_l}\right). \quad (5)$$

Where: $\gamma_1 = 0$.

The linear growth function is used in the case of there being no maximum limit for the time series, and it is calculated according to the following (6):

$$g(t) = (k + a(t)^T\delta)t + (m + a(t)^T\gamma). \quad (6)$$

The seasonal function $F(t)$ is calculated according to the Fourier series, and its mathematical formula is as follows:

$$F(t) = \sum_{n=1}^{N} \left[\alpha_n \cos\left(\frac{2\pi nt}{s}\right) + b_n \sin\left(\frac{2\pi nt}{s}\right)\right]. \quad (7)$$

Where:

- s, the seasonal period of the data,
- N the number of terms in the Fourier series,
- t the time Period, $t = 1,2, \ldots, T$, b_n, α_n Fourier parameters [1].

The special events function $h(t)$ represents the events that affect the time series, and its mathematical formula is:

$$h(t) = Z(t)\,\Sigma. \quad (8)$$

Where:

- Σ_i a parameter given to each holiday,

- $Z(t)$ an indicator denoting whether the time (t) falls within the event period (holiday) and calculates as follows [2]:

$$Z(t) = [1\,(t \in Day_1), \dots, 1\,(t \in Day_l)]. \quad (9)$$

2.2 Estimating the Model Parameters

The Facebook Prophet model is one of the models that deal with smoothing functions, as it includes several smoothing functions namely: trend smoothing functions, seasonal smoothing functions, and holiday smoothing functions. Estimating the model parameters is represented by achieving the Following loss function [3]:

$$Loss\,(\vartheta) = \sum_{t=1}^{T}(Y_t - \hat{Y}_t)^2 + \lambda \sum_{t=1}^{T}|\vartheta_T|. \quad (10)$$

Where:

- λ the amount of penalty imposed on the parameter to avoid overfitting,
- ϑ the vector of parameters for each of the smoothing functions $g(t)$, $F(t)$,$h(t)$, in addition to the variance parameter ${\sigma^2}_{\epsilon}$, where:

$$\vartheta = (\,k, m, \delta, \gamma, \beta, \Sigma, \sigma^2\,).$$

The loss function in (10) can be rewritten as follows:

$$\begin{aligned} Loss\,(\vartheta) = argmin\Big\{ & \sum (Y_t - \hat{g}(t) + \hat{F}(t) + \hat{h}(t))^2 \\ & + \lambda_1 \| \delta \|^2 + \lambda_2 \| \gamma \|^2 \\ & + \lambda_3 \sum \|\alpha_n + b_n\|^2 + \lambda_4 \|\Sigma\|^2 \Big\}, \end{aligned} \quad (11)$$

and in order to achieve the loss function in (11) we use the Limited Memory Broyden, Fletcher, Goldfarb, and Shanno (L-BFGS) algorithm, which gives us the optimal values for the model parameters.

The L-BFGS algorithm is known as one of the memory - constrained Quasi – Newton approximation algorithms, and it has gained wide importance in optimizing objective functions due to its ability to deal with the complexities of nonlinear functions and deal with memory constraints. The basic idea of (L-BFGS) is to use the (curvature Information), which represents the second derivative (Second Derivative Information) of the most recent iterations only, to create a Hessian matrix approximation, as the curvature information from the previous iterations is ignored in order to save good storage space [7].

The Hessian matrix describes the curvatures of nonlinear functions, for numerical optimization, and the Hessian matrix is also called the information matrix of the observations, and the inverse of the Hessian matrix represents the variance-covariance of the estimators of the studied function, and is written in short as (H), and can be represented according to the following [8]:

$$H = \begin{bmatrix} \frac{\partial^2 f}{\partial {x_1}^2} & \frac{\partial^2 f}{\partial x_1 \partial x_2} & \cdots & \frac{\partial^2 f}{\partial x_1 \partial x_n} \\ \frac{\partial^2 f}{\partial x_2 \partial x_1} & \frac{\partial^2 f}{\partial {x_2}^2} & \cdots & \frac{\partial^2 f}{\partial x_2 \partial x_n} \\ \vdots & \vdots & \cdots & \vdots \\ \frac{\partial^2 f}{\partial x_n \partial x_1} & \frac{\partial^2 f}{\partial x_n \partial x_2} & \cdots & \frac{\partial^2 f}{\partial {x_n}^2} \end{bmatrix}_{n \times n}. \quad (12)$$

It can also be written at time r as follows [7]:

$$H_r = \nabla^2 l(\vartheta). \quad (13)$$

The estimation steps according to the L-BFGS algorithm are represented in the following form:

1) Gradient Computation, $l(\vartheta)$. It is a multi-parameter function, which is the vector of partial derivatives of the function at time point r that is to be minimized, since $i = 1,2, \dots, r$, where:

$$\nabla l(\vartheta) = G(r). \quad (14)$$

2) Calculating the update of the approximate (Hessian) Matrix.

The Hessian matrix is updated according to the following relationship:

$$\begin{aligned} H_{r+1} = & \left(I - \mathcal{P}_r S_r {R_r}^T\right) H_r \left(I \right. \\ & \left. - \mathcal{P}_r R_r {O_r}^T\right). + \mathcal{P}_r S_r {S_r}^T \end{aligned} \quad (15)$$

Where:

- R_r the change in the gradient that calculated according to the following:

$$R_r = G_{r+1} - G_r. \quad (16)$$

- O_r: the change in the parameters that represented according to the following:

$$O_r = \vartheta_{r+1} - \vartheta_r. \quad (17)$$

- $\mathcal{P}_r$: the inverse of the product of the change in the parameters and the change in the gradient is calculated according to the following:

$$\mathcal{P}_r = \frac{1}{{R_r}^T O_r}. \quad (18)$$

The inverse of the approximation of the (Hessian) matrix is calculated through the following:

$$H_r = {\mathcal{B}_r}^{-1}. \quad (19)$$

- ${\mathcal{B}_r}^{-1}$ represents the variance-covariance matrix of the parameter estimates at the point (time r).

3) Calculating (search Direction).

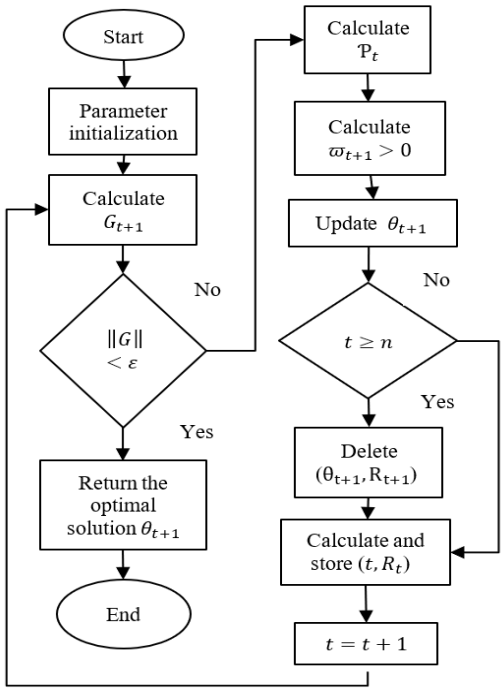


Figure 1: The flow chart of L-BFGS method.

It is a vector that determines the optimal direction for updating the parameters in the optimization process and is calculated using the inverse approximation of the (Hessian) matrix based on the concept of (Limited Memory) and is calculated according to the following formula:

$$\mathcal{P}_r = -\mathcal{B}_r \nabla l(\vartheta_r). \quad (20)$$

- $\mathcal{P}_r$: provides us with information about any parameter that needs to be modified, and it is calculated without the need to store the matrix H_r completely.

4) Updating Parameter ϑ.

The last step is to update the vector of parameters (ϑ) through the following formula:

$$\vartheta_{r+1} = \vartheta_r + \varpi_r \mathcal{P}_r. \quad (21)$$

Where: ϖ_r the value of the (Line Search) and is used to determine the optimal step size (step Size) when updating the parameters in the gradient calculation $L(\vartheta)$).

The appropriate λ value of (regulatory limits) is chosen through the cross- validation (C.V) in a way that achieves the restrictions imposed on each function of the Facebook Prophet model, and these steps continue until the loss function in (10) is achieved [7], [9], [10].

The Flow Chart of the (L-BFGS) method is shown in Figure 1 as follows [10]:

3 THE PRACTICAL APPLICATION

The Prophet model was used in the practical application of the data of the studied phenomenon according to a program written in the R language, the study data represents the consumed quantities of electrical energy in Baghdad Governorate measured in (Kw/h) taken on a daily basis for the period from 1/1/2024 to 12/31/2024. This data was obtained from the Ministry of Electricity/Operation and Control Department, and through the following Figure 2 we show the plot of the study data.

When analyzing the time series according to the studied model, its components become clear to us, such as trend, seasonality, and special events. The following Figure 3 shows this.

Figure 3 shows the presence of a general trend that changes with time, in addition to the clarity of the effect of holidays on the time series data, as we notice the presence of sharp peaks and valleys, and it is also clear to us the presence of the weekly seasonal component, as it appears that there is a pattern that changes with the change of days of the week, and the presence of the annual component in the data is also clear, as we notice the repetition of the pattern during the months of the year, with a sharp rise in the summer months and a sharp decline in the winter months.

When applying the L-BFGS algorithm, we obtained the parameter values shown in Table 1:

Table 1: The estimation of the parameters of the Facebook Prophet.

Parameter	Coefficient
Growth rate k	0.2411
offset parameter m	1.0271
δ represents the amount of increase or decrease in the growth rate	[1,1:30] -8.001, 0.6781, -0.2427, …
β represents the vector of parameters of the Fourier Series	[1,1:74] -0.5451, -0.1083, 0.0047, …

The residuals of the time Series are shown in Figure 4.

The predicted values are Presented in Table 2.

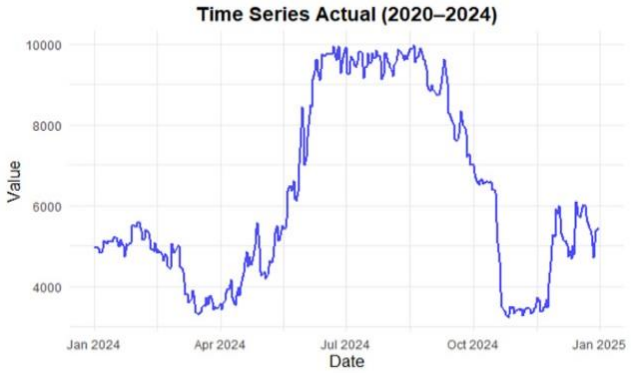


Figure 2: Represents the time series graphically.

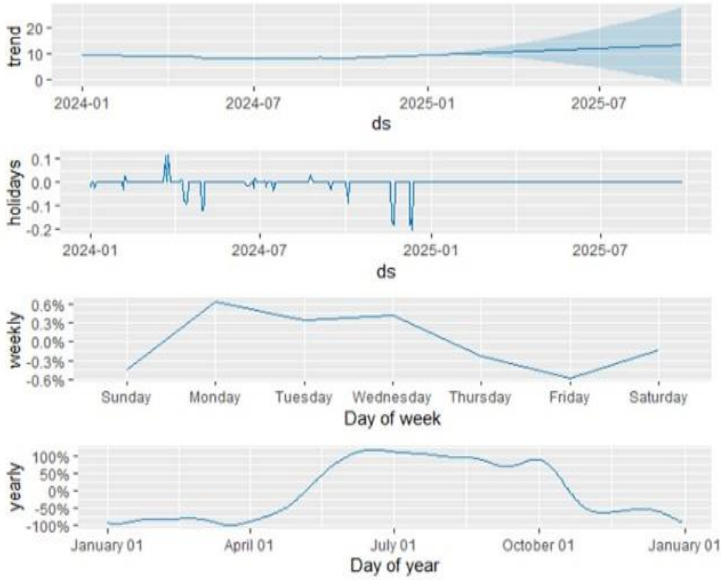


Figure 3: The components of time.

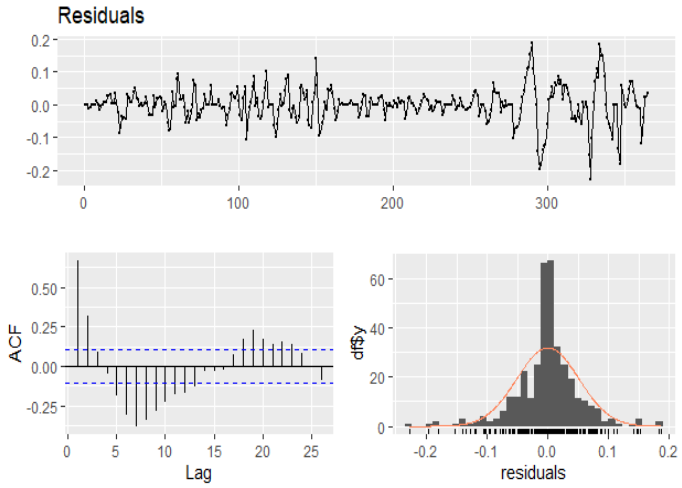


Figure 4: Represents the residuals of the time series, its autocorrelation function, and the shape of its distribution.

Table 2: represents the predictive values according to the FB Prophet model.

Date	Forecast	Date	Forecast
1/1/2025	5285	2/15/2025	11320
1/2/2025	5266	2/16/2025	11476
1/3/2025	5275	2/17/2025	11796
1/4/2025	5337	2/18/2025	11959
1/5/2025	5371	2/19/2025	12166
1/6/2025	5493	2/20/2025	12279
1/7/2025	5553	2/21/2025	12425
1/8/2025	5646	2/22/2025	12662
1/9/2025	5709	2/23/2025	12794
1/10/2025	5801	2/24/2025	13096
1/11/2025	5950	2/25/2025	13209
1/12/2025	6064	2/26/2025	13358
1/13/2025	6273	2/27/2025	13393
1/14/2025	6408	2/28/2025	13454
1/15/2025	6573	3/1/2025	13605
1/16/2025	6695	3/2/2025	13639
1/17/2025	6842	3/3/2025	13850
1/18/2025	7046	3/4/2025	13860
1/19/2025	7198	3/5/2025	13911
1/20/2025	7453	3/6/2025	13851
1/21/2025	7607	3/7/2025	13828
1/22/2025	7787	3/8/2025	13909
1/23/2025	7906	3/9/2025	13885
1/24/2025	8044	3/10/2025	14057
1/25/2025	8239	3/11/2025	14044
1/26/2025	8368	3/12/2025	14092
1/27/2025	8608	3/13/2025	14047
1/28/2025	8728	3/14/2025	14061
1/29/2025	8875	3/15/2025	14202
1/30/2025	8952	3/16/2025	14255
1/31/2025	9052	3/17/2025	14530
2/1/2025	9219	3/18/2025	14633
2/2/2025	9316	3/19/2025	14816
2/3/2025	9544	3/20/2025	14917
2/4/2025	9644	3/21/2025	15092
2/5/2025	9782	3/22/2025	15414
2/6/2025	9850	3/23/2025	15651
2/7/2025	9953	3/24/2025	16139
2/8/2025	10139	3/25/2025	16443
2/9/2025	10255	3/26/2025	16838
2/10/2025	10522	3/27/2025	17137
2/11/2025	10655	3/28/2025	17516
2/12/2025	10834	3/29/2025	18061
2/13/2025	10939	3/30/2025	18497
2/14/2025	11084	3/31/2025	19222

Figure 5 shows the predictions that were reached through the model with the confidence intervals.

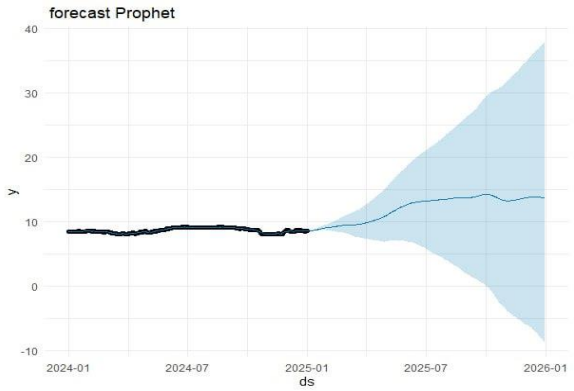


Figure 5: Represents the predictive values of the Facebook Prophet model.

4 CONCLUSIONS

The results confirm that the Facebook Prophet model provides a reliable and effective framework for forecasting electricity consumption in Baghdad Governorate. The model successfully captured the long-term trend, seasonal variations, and the influence of special events, demonstrating its flexibility in handling complex time series data. The close agreement between the predicted and actual values reflects the robustness of the model and its ability to generate accurate forecasts. These findings highlight the potential of Prophet as a valuable analytical tool for supporting electricity demand management and planning. Its structure, which accommodates change points and multiple seasonal patterns, enhances both interpretability and predictive accuracy. Future work may focus on improving the model's performance by integrating Prophet with other statistical or machine learning techniques and incorporating additional explanatory factors to further refine forecasting precision and applicability in real-world energy analysis.

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Investigation of Nitrogen Doping Effects on the Performance of Graphene in Lithium-Ion Batteries Using Density Functional Theory

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Keywords: Graphene, Lithium-Ion Batteries, Doping N-Defect Graphene, Anode Materials, DFT.

Abstract: We performed first-principles calculations using density functional theory (DFT) with the CASTEP code in Materials Studio to investigate the adsorption behaviour of lithium (Li) on graphene featuring single defects. Our study employed the generalized gradient approximation (GGA-PBE) to analyse the adsorption and diffusion characteristics of Li on three distinct graphene structures: pristine graphene, graphitic nitrogen-doped graphene (NG), and pyridinic nitrogen-doped graphene (NG1). The results indicated that Li diffusion occurs significantly faster on N-doped graphene compared to pristine graphene. Specifically, the calculated diffusion energy barriers were found to be 0.82 eV for pristine graphene, 1.83 eV for NG, and 0.65 eV for NG1. This suggests that NG1, with its lower energy barrier, facilitates Li movement more efficiently than the other structures. Furthermore, NG1 demonstrated a remarkable theoretical specific capacity of 453.88 mAh/g, underscoring its potential as an advanced anode material for lithium-ion batteries (LiBs). Overall, our findings highlight that nitrogen-doped defect graphene not only improves lithium diffusion kinetics but also enhances the overall capacity for lithium storage, making it a highly promising candidate for next-generation LiB applications.

1 INTRODUCTION

In recent years, lithium-ion batteries (LIBs) have gained considerable attention due to their high energy density and excellent efficiency. Consequently, they are widely used in portable electronic devices, including smartphones, tablets, laptops and other mobile gadgets [1]. LIBs are regarded as one of the most promising energy storage technologies, owing to their advantages such as high efficiency, compact size, lightweight nature, temperature responsiveness, and ease of maintenance [2].

Among various anode materials, graphite remains the most widely used option, boasting a specific capacity of 372 mAh/g [3]. Carbon is a versatile element, forming structures that encompass a range of dimensionalities in nature. Until a few decades ago, only three carbon allotropes were commonly recognized: graphite, diamond and amorphous carbon [4].

Graphene, a single layer of graphite, can be isolated from bulk material or synthesized as a monolayer. Its carbon atoms are arranged in a flat, sheet-like hexagonal lattice, forming a honeycomb pattern with a bond angle of 120° and an interatomic distance of 1.42 Å [5]. As a two-dimensional (2D) sp^2-hybridized carbon allotrope, graphene has attracted immense interest due to its unique electronic properties, such as the half-integer quantum Hall effect, high electron mobility, and massless Dirac fermions [6]. The successful isolation of graphene by Andre Geim and Konstantin Novoselov at the University of Manchester in 2004 sparked a surge of global research interest [7]. Since then, numerous studies have explored its potential applications as an anode material for LIBs [8]-[13].

This growing interest is driven by graphene's ability to adsorb lithium on both surfaces, with its available surface area for lithium storage far exceeding the interlayer spacing of graphite. Its flat, monolayer structure facilitates rapid lithium diffusion, making graphene a prominent subject in theoretical investigations as a prospective anode material for LIBs [14]-[17].

Moreover, doped graphene has been successfully synthesized, with nitrogen-doped (N-doped) graphene initially produced using the chemical vapor deposition (CVD) method [18]. Recent developments have introduced various innovative techniques for fabricating N-doped graphene [19], [20].

Investigations into N-doped graphene as an anode material for LIBs highlight several advantages [21]. Extensive research indicates that N-doped graphene is a promising anode candidate, primarily due to the higher electronegativity of nitrogen compared to carbon and the hybridization between nitrogen's lone pair electrons and the graphene lattice [22].

In this study, we investigate lithium (Li) diffusion across a graphene monolayer using density functional theory (DFT) calculations. We find that the diffusion energy barrier for pristine graphene is significantly high. To lower this barrier, we examine Li diffusion through graphene containing commonly observed defects. The energy barriers for doped graphene with single defects are also calculated, revealing that such defects reduce the diffusion barriers.

2 COMPUTATIONAL DETAILS

Since the formulation of two foundational theorems by Hohenberg and Kohn in 1964 [23], density functional methods have grown increasingly popular over the past decade [24]. These theorems assert that the ground state energy of a system is determined by a unique electron density functional, under the assumption that the "true" computed density minimizes the system's total energy. A practical approach to obtaining this density was subsequently introduced by Kohn and Sham, involving an iterative solution of single-electron wave equations. This approach incorporates three key potentials: exchange-correlation effects, coulomb repulsion among electrons and other particles in the system, and interactions between electrons and nuclei [25]. As the goal is to determine the ground-state electron density, Kohn and Sham showed that the complex many-body Schrödinger equation could be simplified to a single-electron (1), [26].

$$\left[\frac{h^2}{2m}\nabla^2 + V(\mathbf{r}) + V_H(\mathbf{r}) + V_{\mathrm{XC}}(\mathbf{r})\right]\psi_i(\mathbf{r}) = \varepsilon_i\psi_i(\mathbf{r}) \quad (1)$$

The Kohn–Sham equation yields single-electron wave functions, each dependent on only three spatial coordinates. The potential V on the left-hand side of the Kohn–Sham equation represents the interaction between an individual electron and a set of atomic nuclei.

CASTEP is employed to carry out periodic DFT calculations. The generalized gradient approximation (GGA) exchange-correlation functional developed by Perdew, Burke, and Ernzerhof (PBE) is utilized [27]. The convergence criterion for the electronic self-consistent loop is set to 10^{-6} eV, and the wave functions are represented using plane waves with a cutoff energy of 450 eV. Structural relaxation continues until the self-consistent force on each atom is reduced below 0.03 eV/Å $^{-1}$. To eliminate artificial interactions due to periodic boundary conditions, a vacuum spacing of 15 Å is introduced perpendicular to the surface. For Brillouin zone integration, a 3×3×1 Γ-centered Monkhorst–Pack (MP). The N-doped graphene system modeled in this study was assigned a doping concentration of approximately 2.04 at%, which aligns with experimental reports [28]-[30]. To compare the binding strength of Li in graphene-based systems, the adsorption energy (E_{ad}) was calculated using the following expression the (2), [31]:

$$E_{ad} = \left(E_{\mathrm{Total}} - E_g - nE_{Li}\right)/n_{Li} \quad (2)$$

Here, E Total represents the total energy of the Li–graphene system, E Li denotes the total energy of an isolated Li atom, n is the number of adsorbed atoms, and Eg corresponds to the total energy of the isolated graphene sheet.

A key parameter for evaluating electrode performance is the theoretical capacity. The theoretical capacity of the material is determined using the (3), [32].

$$Q = 1000 \times F \times z\frac{n}{M_a} \quad (3)$$

In this context, F, z, n , and Ma represent the Faraday constant (F=26.801 Ah/mol), the number of valence electrons (z=1 for Li), the number of intercalated Li ions (n), and the molar mass of the host system without the ion (Ma) [33].

Surface migration of Li ion on graphene structures ionic conductivity, a critical factor that directly influences the rate performance of LIB electrode materials, is governed by Li ion migration. Rapid Li diffusion plays a vital role in ensuring fast charge–discharge cycles and achieving high power densities in batteries. The study of the diffusion properties and the activation energies of Li adsorbed on the surface was performed with the nudged elastic band method (NEB) [34], [35].

3 RESULTS AND DISCUSSION

3.1 Graphene Doping with Nitrogen Atom

The computer models of graphene structures are displayed in Figure 1. The two bonding configurations that a nitrogen atom can primarily

exist in within the carbon lattice when doped into graphene are graphitic and pyridinic. To represent graphitic-N (NG) and pyridinic-N (NG1), geometric structures of three potential configurations were constructed and optimized. The pyridinic-N bonding arrangement is stable when a monovacancy is present. NG1 was produced by removing one carbon atom and replacing it with one nitrogen atom, resulting in a mono-vacancy defect. Nitrogen, possessing the electronic configuration $2s^2 2p^3$, introduces three valence electrons to form σ-bonds with neighboring carbon atoms when incorporated into a graphitic nitrogen configuration (NG). A fourth electron delocalizes to participate in π-bonding, while the remaining unpaired electron partially occupies the π* antibonding states within the conduction band [36].

3.2 Li Adsorption Sites and Adsorption Energies

To identify the most favorable lithium adsorption site on each graphene-based structure, three possible adsorption configurations were considered, as illustrated in Figure 1 the center of the hexagonal ring (H site), the top of a carbon or dopant atom (T site) and the bridge site above the midpoint of a C–C or C–N bond (B site). The adsorption energy for lithium was calculated using the standard adsorption energy (2) to assess its interaction with doped graphene surfaces. A summary of the computed adsorption energies for each site and structure is presented in Table 1. Notably, although lithium was initially positioned at T, B, and H sites, structural relaxation consistently led to convergence at the H site, indicating its energetic preference. It is important to note that in periodic systems, long-range elastic interactions can introduce energy variations due to the spurious interactions between defects and their periodic images, potentially affecting the calculated adsorption energies. The calculated adsorption energy for the NG1 configuration is -1.24 eV, which is notably more negative than that of pristine (undoped) graphene, recorded at -1.11 eV. This indicates a stronger interaction between lithium atoms and the NG1 surface. The enhanced binding energy can be attributed to the presence of surface dangling bonds formed as a result of vacancy defects, which serve as favorable anchoring sites for lithium adsorption. As a result, Li atoms tend to remain stably positioned at the center of the defect site. Among the investigated adsorption sites, the H site located at the center of the hexagonal ring emerges as the most energetically favorable position for lithium, in agreement with previous studies [37]. The relatively weak interaction between lithium and NG is primarily due to nitrogen high electronegativity (3.04), which attracts electrons from adjacent carbon atoms and reduces Li ability to donate charge in its vicinity. This electron-rich environment causes Li to shift away from the nitrogen site after adsorption. In contrast, although NG1 also contains nitrogen, the presence of vacancy-induced defects enhances Li binding by offering unsaturated, reactive sites. Figure 2 displays the optimized geometries of Li adsorption on graphene, NG, and NG1, along with the nearest atomic distances. In all cases, Li is initially positioned approximately 1.251 Å above the graphene plane.

3.3 Surface Migration of Li Ions on Graphene Structures

The diffusion energy barriers for lithium migration were evaluated across all investigated graphene-based structures. To enable a consistent comparison, we focused on the minimum energy barriers along diffusion pathways leading to the most energetically favorable adsorption sites. Figures 3, 4, and 5 illustrate the calculated diffusion energy barriers and the corresponding migration paths. For pristine graphene, the diffusion energy barrier was calculated to be 0.82 eV, aligning well with values previously reported in the literature [37]. Among the doped structures, NG1 demonstrated the most favorable lithium diffusion behavior, with a significantly lower energy barrier of approximately 0.65 eV (see Table 2). This enhanced mobility can be attributed to electron–electron repulsion between the dopant atom and the lithium ion, which tends to push Li away from the nitrogen site and toward energetically preferred adsorption positions. In contrast, NG exhibited a relatively higher diffusion barrier of approximately 1.83 eV. This is largely due to the influence of nitrogen doping, which eliminates carbon-centered radicals near defect sites and thereby hinders lithium migration [38]. Despite these variations, all structures maintained acceptable ionic conductivity with manageable energy barriers along their respective migration pathways.

Table 1: The most stable location for Li adsorption, and the adsorption energy (E_{ad}).

Structure	Most stable adsorption site	Adsorption energy(eV)	Theoretical studies [22]	Distance(Å)
Graphene	H	-1.11	-0.98	2.251
NG	H_1	-1.12	-0.95	2.211
NG1	H_2	-1.24	-1.37	2. 171

Table 2: The diffusion barrier height ΔE_b(eV).

Structure	Diffusion barrier height ΔEb(eV)
Graphene	0.82
NG	1.83
NG1	0.65

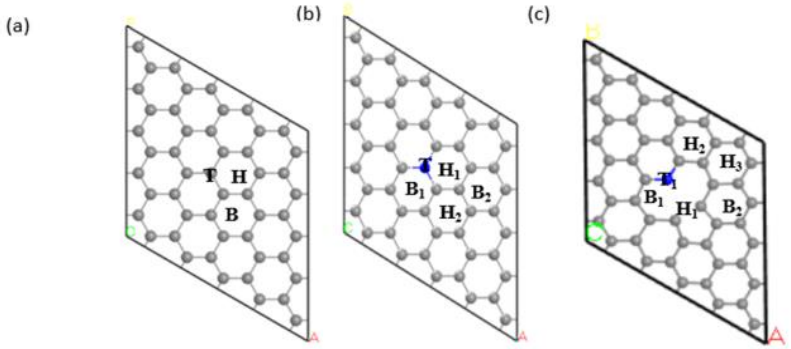


Figure 1: Optimized structures of a) graphene, b) NG, c) NG1.

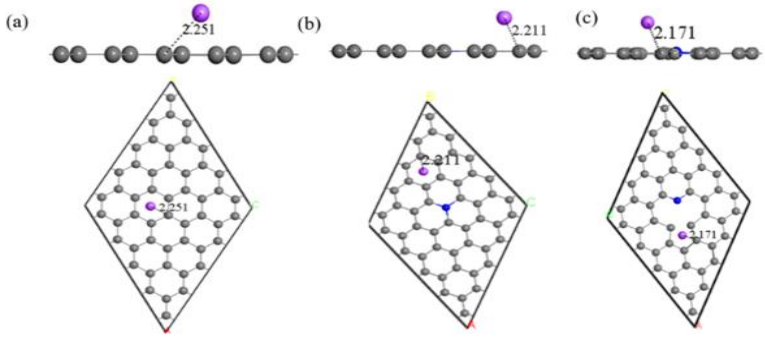


Figure 2: Optimized interaction geometry of Li and a) graphene, b) NG, c) NG1.

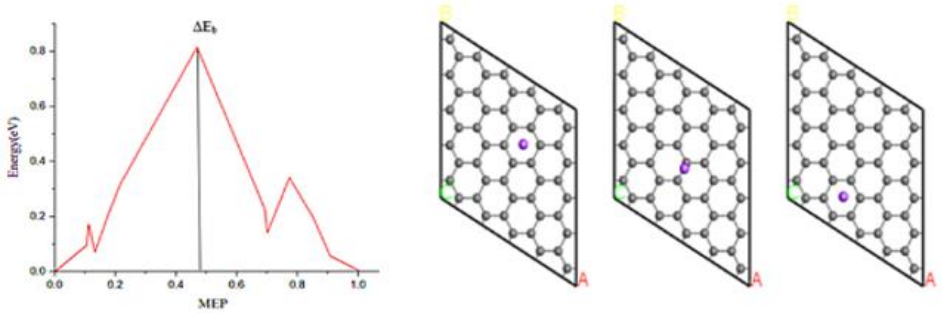


Figure 3: The energy barrier (ΔE_b) for graphene.

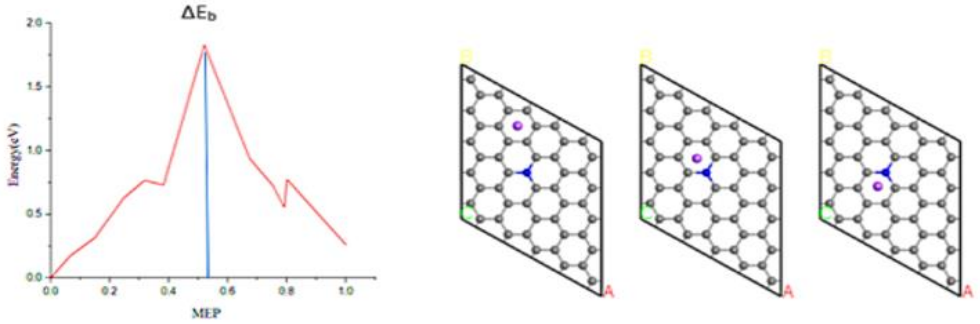


Figure 4: The energy barrier (ΔEb) for NG.

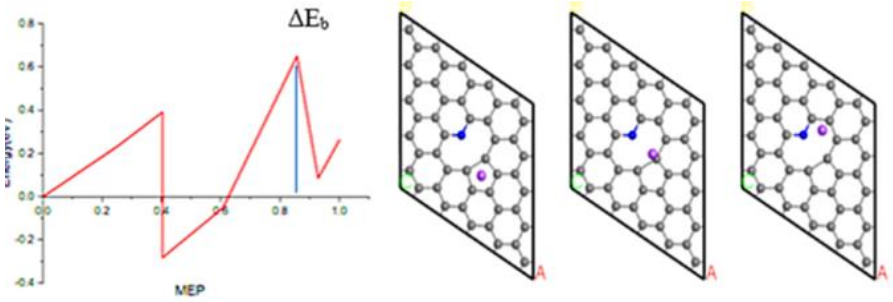


Figure 5: The energy barrier (ΔE_b) for NG1.

3.4 Theoretical Capacity

The lithium storage capacity of an anode material is a critical parameter in determining its applicability for lithium-ion batteries (LiBs). To further elucidate the lithium storage mechanism in heteroatom-doped defect graphene, the structural configuration of lithium atoms was analyzed. Figure 6 illustrates the optimized geometry of ten lithium atoms (n = 10) adsorbed on the doped-defect graphene surface. Initial investigations showed that a single Li atom tends to stabilize at the hollow sites of the graphene lattice [38]. To determine the maximum lithium storage capacity, additional Li atoms were progressively introduced onto the surface of doped-defect graphene (NG1) structure. The theoretical specific capacity was calculated using (3), with NG1 exhibiting the highest capacity of 453.88 mAh g^{-1}. These theoretical values are supported by experimental findings, which report exceptionally high capacities of approximately 199 mAh g^{-1} for N-doped graphene and 235 mAh g^{-1} for B-doped graphene at a current density of 25 A g^{-1} corresponding to a full charge time of about 30 seconds [39]. To evaluate structural integrity, the bond lengths of N–C (dopant–carbon) and C–C were measured following the adsorption of ten Li atoms, as summarized in Table 3. For the NG1 structure, only minimal deformation was observed. The average C–C bond length exhibited a slight decrease of approximately 2.09%, while the N–C bond length increased by 4.51% relative to their pristine values. These minor changes indicate that NG1 maintains structural stability under high lithium loading.

Table 3: N-C and C-C bond lengths before and after Li adsorption for NG1.

Before Adsorption (n = 0)			After Adsorption (n = 10)	
Structure	d(N-C)	d(C-C)	d(N-C)	d(C-C)
NG1	1.33	1.43	1.39	1.40

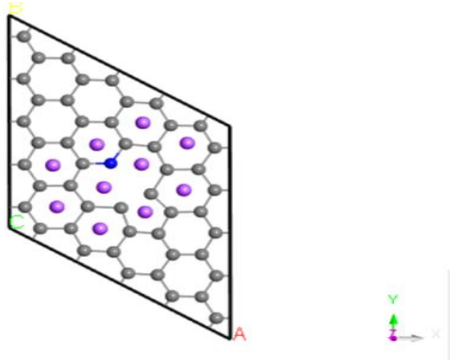


Figure 6: The optimized geometries of ten Li atoms adsorbed on NG1.

4 CONCLUSIONS

In this study, comprehensive density functional theory (DFT) calculations were conducted to explore the lithium adsorption, diffusion, and desorption behaviors on pristine graphene, nitrogen-doped graphene, and nitrogen-doped defect graphene. The presence of structural defects was found to significantly enhance lithium adsorption by creating energetically favorable sites. Moreover, nitrogen doping further strengthens the interaction between lithium and the graphene surface.

Among the examined structures, N-doped defect graphene (NG1) exhibited the lowest energy barriers for both lithium diffusion and desorption, suggesting its potential for high-rate charge/discharge performance in lithium-ion batteries (LIBs). The theoretical specific capacity of NG1 was calculated to be as high as 453.88 mAh g^{-1}, indicating strong promise for next-generation anode materials. Overall, these findings contribute to a deeper understanding of lithium–graphene interactions and offer a foundation for the rational design of high-capacity, stable anode materials for advanced LIB applications.

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Results of Research on the Technological Process of Cattle Manure Utilization in a Biogas Plant

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Keywords: Biogas, Anaerobic Digestion, Manure Utilization, Biofertilizers, Renewable Energy, Sustainable Agriculture, Circular Economy, Methane Production, Environmental Protection, Digestate Utilization.

Abstract. Amid the growing demand for sustainable and environmentally friendly energy sources, biogas plants represent a promising solution for processing organic waste. This work examines the potential for biogas production under mesophilic temperature conditions and the creation of new renewable energy sources through anaerobic fermentation. The manure treatment process not only enables the production of methane as a valuable energy resource, it also yields biofertilizers that can be used in agriculture. As a result, the use of biogas helps reduce greenhouse gas emissions and improve soil quality, making it an important element in the transition to sustainable farming practices and environmental protection. Experimental studies were carried out on a biogas plant developed at the Department of Machinery and Equipment in Agribusiness of Kazan State Agrarian University, resulting in the production of combustible biogas. The purpose of this study is to conduct a comparative analysis of the theoretical and experimental biogas yields and to assess the quality of the resulting products. The research followed a standard methodology at mesophilic fermentation temperatures ranging from 25 to 35 °C.

1 INTRODUCTION

Environmental protection and the conservation of natural resources are among the most significant global challenges of our time, the solution to which requires coordinated action at the international level. Agriculture plays a key role in this process: it not only ensures food security but can also become a source of renewable energy through biomass processing. One of the most promising areas in sustainable energy is biogas production, which results from the anaerobic decomposition of organic matter by a complex microbiological community. This process includes the sequential stages of hydrolysis, acidogenesis, acetogenesis, and methanogenesis, during which complex organic compounds such as proteins, fats, and carbohydrates are converted into methane (CH_4, 50–85% of the total biogas volume), carbon dioxide, and other associated gases. Substrates for biogas plants include various types of organic waste-agricultural residues, manure, plant biomass, and municipal waste-making this technology both environmentally and economically attractive. In recent decades there has been steady growth in biogas production in many countries, including Russia, where its potential has not yet been fully realized but already shows significant promise for reducing dependence on fossil fuels and cutting greenhouse gas emissions [1], [2], [3].

The rational use of organic fertilizers in the agro-industrial complex is a top-priority task directly tied to the sustainable development of agriculture and the maintenance of soil fertility. Under current conditions of arable land degradation and declining humus content, the use of organics is becoming a strategic direction supported at the state level. Organic fertilizers not only supply plants with essential nutrients but also improve soil physico-chemical properties, increasing its water-holding capacity and biological activity. However, their use poses technological challenges because, along with beneficial substances, weed seeds and pathogenic microflora are introduced into the soil. Studies show that one tonne of fresh manure contains from 200 to 700 thousand viable weed seeds, and in bedding manure this figure rises to 5–7 million seeds per tonne. In parallel, organic fertilizers contain vast numbers of microorganisms - more than 1 million

bacteria per tonne - among which there may be pathogens dangerous to animals and humans. To neutralize these negative factors, agricultural producers are forced to apply additional protective measures, including treatment with pesticides and herbicides, which significantly increases the cost of agricultural products and creates additional burdens on agro-ecosystems [4].

One of the most effective technologies for converting manure into high-quality biofertilizer is anaerobic fermentation. This process not only ensures deep decomposition of organic matter with the parallel production of biogas as a renewable energy source, it also significantly improves the agrochemical characteristics of the final product. During methane fermentation in biogas plants there is complete destruction of weed seeds and pathogenic microorganisms, which fundamentally distinguishes the processed manure from the initial raw material in terms of biological safety. The resulting biofertilizers possess a unique set of properties: an absence of phytopathogens and weed seed banks; a marked reduction in emissions of volatile organic compounds responsible for unpleasant odors; and the presence of highly active beneficial microflora that stimulates plant growth and increases disease resistance. Key agronomic advantages include higher resistance to leaching of macro- and microelements from the soil profile, an optimal form of available nitrogen with prolonged action, and the ability to improve soil structure and enhance humification processes. Collectively, these factors help restore and maintain the ecological balance of agrocenoses.

Cattle manure is a valuable organic fertilizer composed of a complex mixture of solid and liquid fractions containing a suite of nutrients in bioavailable forms [5]. Its chemical composition features high contents of organic matter, nitrogen, phosphorus, potassium, and trace elements, making it an effective means of increasing soil fertility. Processing manure fosters an active microbial community that improves soil structure, enhances humification, and raises biological activity. The use of this type of organic amendment is strictly regulated by standards that account for soil-climatic conditions, the hydrological regime of territories, and safety indicators including heavy metal content and other controlled contaminants. Cattle manure is widely used in agriculture to boost crop yields, in landscape construction for creating green spaces, and as an important component in land reclamation and the restoration of degraded soils. Its use is particularly important in ornamental plant nurseries and for establishing resilient lawns, where it serves as an effective and environmentally safe component of soil mixtures [6], [7].

The objective of this work is to study the processes of producing biogas and biofertilizers in biogas plants and to evaluate the quality of the obtained products.

2 MATERIALS AND METHODS

Experimental studies were conducted under laboratory conditions using a specially designed small-volume biogas unit (Fig. 1), with particular attention paid to temperature control as a critically important parameter for the effective operation of the methanogenic microbial consortium. Special emphasis was placed on the smooth adaptation of mesophilic bacterial cultures to changing temperature conditions, since sharp fluctuations can significantly reduce biogas productivity [8], [9]. A stable temperature in the bioreactor of 35–37 °C was maintained using an electric heating element rated at 0.8 kWh. The temperature control system accounted for ambient laboratory temperature, the initial temperature of the feedstock, and the thermal characteristics of the organic wastes themselves, providing optimal conditions for microbial metabolic activity and stable biogas production. The amount of heat required to warm the biomass and maintain mesophilic fermentation in the bioreactor is determined by the following expression [10]:

$$Q = G_{bio} \cdot c_{bio}\left(t_{inital} - t_{ferm}\right). \quad (1)$$

Where:

- G_{bio} – biomass, kg;
- c_{bio} – specific heat capacity of the biomass, $\frac{J}{kg}$;
- $t_{initial}$ – initial temperature of the biomass at the bioreactor inlet, ºC;
- t_{ferm} – fermentation temperature in the bioreactor, 35 ºC.

The experimental program comprised several stages. First, a laboratory analysis of the feedstock composition was performed (moisture, ash content, pH, and mass fraction of organic matter). After assembling the experimental setup, a comprehensive leak test of all joints and assemblies was carried out, along with verification of the measuring systems and control automation. The initial startup was performed in test mode using water instead of biomass, which made it possible to check tightness, mixer operation, and the circulation loop without the risk of biological contamination. During a 24-hour no-load run,

temperature parameters were monitored, pressure sensor readings were recorded, and the stability of all process units was checked. The resulting data were used to calibrate the temperature controllers and configure the automatic system for maintaining optimal process parameters prior to loading the main biomass. Anaerobic fermentation was then carried out in the small-volume biogas unit at 35 °C. The setup operated in batch mode with a single loading of cattle manure and a 25-day anaerobic fermentation cycle. To ensure optimal conditions for bioconversion, cyclic mixing of the substrate with a frame mixer was applied four times a day for 1 minute per cycle, which maintained homogeneity with minimal energy consumption. The mesophilic temperature regime (35±0.5 °C) was maintained with a precision temperature control system ensuring uniform heating of the entire biomass volume. These parameters promoted: effective dehelminthization due to prolonged thermal exposure at all parasite life stages; intensive deodorization thanks to the prevention of localized anaerobic zones and uniform release of volatiles; and complete inactivation of weed seeds (99.7% efficiency) due to the combined effects of temperature, mechanical stress, and microbial metabolites. Regular mixing simultaneously optimized mass transfer, prevented phase separation and crust formation, and improved substrate accessibility for hydrolytic and acetogenic bacteria at the initial stages and for methanogenic archaea at the final stage. The results show that the selected regime (temperature, mixing frequency, and duration) ensures not only effective sanitization of the organic substrate but also optimal conditions for maximum biogas productivity and a stable fertilizer product with improved agrochemical characteristics.

Intensification of intracellular metabolic processes plays an important role in optimizing temperature regimes of bioconversion, since the activation of microbial enzyme systems depends directly on reaching and maintaining thermodynamically favorable conditions. This acceleration of biochemical transformations provides: rapid attainment of optimal temperature throughout the substrate thickness due to exothermic reactions of microbial metabolism; a reduced lag phase for microbial consortium adaptation to the substrate; and a 15–20% reduction in overall organic waste processing time relative to standard regimes. The physico-chemical mechanisms include increased heat release due to activation of glycolytic and proteolytic catabolic pathways, especially important when processing recalcitrant substrates. In practice, this optimization not only increases the biodegradation rate by 25-30%, it also substantially improves the quality of the final product – higher degrees of humification, increased contents of plant-available macroelements (N, P, K), and complete inactivation of pathogenic microflora. A synergistic effect is achieved between process energy efficiency (12–15% lower heating energy) and the environmental performance of the resulting biofertilizer (heavy metal contents 1.8–2.3 times below permissible limits).



Figure 1: Small-volume biogas unit: 1 – reactor; 2 – small gasholder; 3 – burner; 4 – electric contact pressure gauge; 5 – gasholder; 6 – bimetal thermometer; 7 – temperature controller; 8 – OWEN PR 110 programmer; 9 – safety valve.

During the experiment, daily changes in key parameters such as temperature, pressure, and biogas production were recorded. A gas meter measured the volume of biogas produced by the system, allowing analysis of process efficiency, and an electromechanical pressure gauge was used for accurate pressure measurement. The methane concentration of the biogas entering the gasholder was determined using a KOMETA‑M gas analyzer.

The kinetics of biogas formation during anaerobic processing of organic waste can be modeled mathematically by a system of stoichiometric equations accounting for:

$$C_aH_bO_cN_d + nH_2O \rightarrow xCH_4 + yCO_2 + wNH_3 + vC_5H_7O_2N + Q, \quad (2)$$

where:

- $H_bO_cN_d$ – is the chemical composition of the processed biomass;
- H_2O – moisture content;
- CH_4 – methane formation;
- CO_2 – carbon dioxide formation;
- NH_3 – ammonia formation;
- $C_5H_7O_2N$ – dry residue after complete decomposition;

- Q – thermal energy released during the reaction;
- n, x, y, w, z – stoichiometric coefficients.

The resulting biofertilizer was subjected to chemical and microbiological analyses at the Tatar Interregional Veterinary Laboratory using standard methods. Quality indicators of the digested biomass were determined, including agrochemical, sanitary-parasitological, and microbiological characteristics.

3 RESULTS

The chemical composition of cattle manure depends on several factors. First, the feed given to the animals significantly affects manure composition. Different feeds contain different proportions of carbon, nitrogen, and other elements, which is reflected in the chemical composition of the manure. In addition, the type of bedding used in housing can influence waste composition [11]. The method of manure storage is also important, since decomposition and degradation processes during storage change element contents. On average, fresh cattle manure contains 61% carbon (C), 12% oxygen (O), 1% sulfur (S), 8% hydrogen (H), and 18% nitrogen (N) on an ash-free basis.

The complete anaerobic decomposition of fresh cattle manure can be described as the transformation of organic matter into the main gaseous products. During the biochemical transformations, complex organic compounds that constitute the basis of manure break down to form methane and carbon dioxide as the principal components of biogas, as well as ammonia as a product of decomposition of nitrogen-containing substances. This transformation is characterized by a specific ratio of gases formed, reflecting the elemental balance in the initial organic material. It should be noted that the actual decomposition process may differ from the theoretical model due to incomplete degradation of recalcitrant compounds, accumulation of intermediate metabolites, and characteristics of the microbial community under specific digestion conditions [12].

$$C_{0,61}H_{0,08}O_{0,12}N_{0,18}S_{0,01} + 0{,}77H_2O \rightarrow 0{,}275NH_4^+ + 0{,}5HCO_3^- + 0{,}413CO_2 + 0{,}571CH_4 + 0{,}011H_2S \quad (3)$$

From the presented chemical reaction it follows that the decomposition of 1 gram of ash-free organic matter produces 0.413 grams of carbon dioxide (CO_2) and 0.571 grams of methane (CH_4).

The theoretical yield of biogas from 1 tonne of fresh cattle manure under mesophilic fermentation is illustrated in Figure 2, showing the potential amount of biogas that can be produced by anaerobic decomposition of the manure's organic matter.

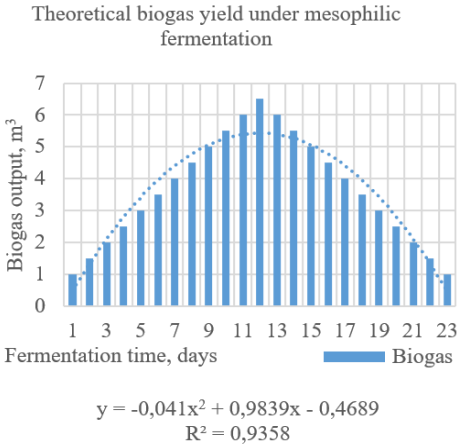


Figure 2: Theoretical biogas yield under mesophilic fermentation.

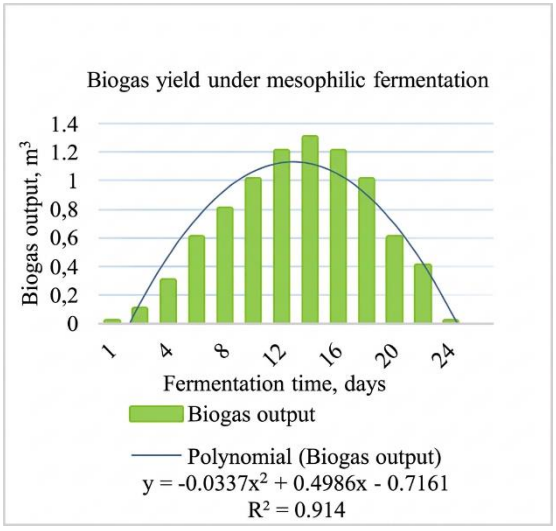


Figure 3: Biogas yields under mesophilic fermentation.

In experimental studies of anaerobic digestion of cattle manure in the small-volume biogas unit operating in mesophilic mode, a methane concentration of 68% was recorded. The optimal calculated parameters and characteristics of the biogas unit developed for farm households were evaluated. This value indicates high methanogenesis efficiency, likely due to optimal microbial operating conditions such as temperature and pH. The averaged test results presented in Figure 3 show the

dependence of gas volume on process duration under mesophilic digestion.

The results of the analysis of cattle manure samples included an assessment of moisture and dry matter content. Moisture was 83.14%, indicating high water content, and dry matter was 16.6%. These data emphasize substantial moisture, which can affect further processing and use.

Analysis of the agrochemical, sanitary-parasitological, microbiological characteristics and quality indicators of the resulting biofertilizer, performed in accordance with GOST R 53117-2008 “Organic fertilizers based on livestock waste” showed the following. The pH of the saline extract was 7, within the norm (6-8,5). The mass fraction of organic matter reached 81%, exceeding the minimum allowable level of 70%.

Sanitary-parasitological tests revealed no cysts of intestinal pathogenic protozoa and no helminth eggs, meeting the established requirements. Quality indicators were: moisture 83%, ash 19%; total nitrogen, potassium, and phosphorus contents of 0.7%, 0.55%, and 2.7%, respectively – each above minimum requirements. Microbiological indicators showed a coliform index and enterococci index of 1 (within the norm of 1-9), while clostridia and pathogenic microorganisms were not detected, complying with safety standards.

4 DISCUSSIONS

The diagram “Biogas yield under mesophilic fermentation” (Figure 2) shows the dynamics of biogas output over time, with a maximum around 1,3 reached between days 12 and 16. During this period, biogas production is most active, after which it declines, reaching minimum values by day 24. Such a curve, which resembles a normal distribution with a mid-cycle peak, can be useful for optimizing system operation – boosting output during decline periods and analyzing factors that reduce production. The gas composition analysis demonstrated a low content of carbon dioxide and other impurities, making it more suitable for energy use. The studies confirmed the feasibility of anaerobic utilization of agricultural organic waste. A combustible gas was obtained, indicating the potential effectiveness of biogas units for processing agricultural waste. The analysis of agrochemical, sanitary-parasitological, and microbiological characteristics of the biofertilizer performed in accordance with GOST R 53117-2008 confirmed its high promise and compliance with standards.

5 CONCLUSIONS

The study confirmed the effectiveness of anaerobic digestion of cattle manure under mesophilic conditions (35 °C) for simultaneous biogas and biofertilizer production. The methane content reached 68 %, indicating stable methanogenesis, while the resulting digestate met GOST R 53117-2008 standards - with 81 % organic matter, neutral pH (7.0), and optimal contents of N (0.7 %), P (2.7 %), and K (0.55 %). Sanitary and microbiological analyses showed full pathogen and helminth inactivation, ensuring biosafety.

Technologically, maintaining a stable mesophilic temperature and periodic mixing improved biogas yield and reduced processing time by 15-20 %. This demonstrates that well-controlled small biogas units can achieve high energy efficiency and process reliability for decentralized farms.

Environmentally, anaerobic digestion eliminates odor and pathogens, reduces greenhouse gas emissions, and produces a biofertilizer that enhances soil fertility and humus balance. Economically, the process enables waste-to-energy conversion, cutting disposal costs while generating renewable energy and valuable fertilizers.

Sanitary, parasitological, and microbiological analyses (coliform and enterococci indices at level 1, absence of pathogens) confirmed its safety. Peak biogas yield (~1.3) was recorded on days 12-16 of mesophilic digestion. The results demonstrate the high efficiency of anaerobic waste digestion technology for the simultaneous production of high-quality fertilizer and energy-rich biogas.

Overall, anaerobic manure treatment under controlled mesophilic regimes is a sustainable, low-cost, and ecologically safe technology that supports renewable energy development and soil restoration. Future work should optimize energy balance and test co-substrates to further increase methane productivity.

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Reduction of the Carbon Footprint of Thermal Power Plants Through the Implementation of Energy-Efficient Technologies

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Keywords: Kazakhstan, Greenhouse Gas Emissions, Thermal Power Plants (Tpps), Coal-Based Energy, Carbon Footprint, Decarbonization, Energy Efficiency, Equipment Modernization, Renewable Energy Sources (RES).

Abstract: The article addresses the issue of high greenhouse gas emissions in Kazakhstan, where the energy sector - primarily based on coal-fired thermal power plants - accounts for up to 80% of total emissions. Data are presented on CO_2 emission dynamics, along with the methodology for their calculation in accordance with international standards such as the GHG Protocol and ISO 14064 (Scope 1–3 categories). Special attention is given to the assessment of the carbon footprint of thermal power plants and the necessity of reducing emissions in order to meet the nationally determined contributions under the Paris Agreement. The paper highlights the worn-out condition of most power plant equipment and the resulting increase in carbon load. Modernization pathways are discussed, including improvements in thermal efficiency, the implementation of cogeneration and waste heat recovery systems, process digitalization, and the transition to cleaner types of fuel. The conclusion emphasizes that reducing the carbon footprint of thermal power plants is a key prerequisite for the sustainable development of Kazakhstan's energy sector and requires comprehensive measures, including international investment, the deployment of renewable energy technologies, and the training of qualified personnel for the new energy industry.

1 INTRODUCTION

The global transition toward low-carbon development presents Kazakhstan with both a challenge and an opportunity to modernize its industrial and energy systems. Decarbonization today is not only a response to environmental imperatives but also a strategic pathway for technological renewal, competitiveness, and economic diversification. In this context, studying advanced international practices - such as carbon capture, utilization and storage (CCUS), hydrogen energy, and clean industrial technologies - provides valuable guidance for shaping Kazakhstan's sustainable energy trajectory.

Thermal power plants remain the backbone of Kazakhstan's power system and, simultaneously, the primary source of anthropogenic carbon dioxide emissions. The country's historical reliance on abundant coal reserves ensured energy independence but created a generation structure with high carbon intensity. Coal-based plants, often equipped with outdated technologies and low efficiency, produce the majority of national emissions. Reducing their carbon footprint is therefore critical for achieving the country's long-term climate goals and ensuring energy security.

Under the Paris Agreement, Kazakhstan has pledged to cut its greenhouse gas emissions by 15% by 2030 (unconditionally) and by up to 25% with international support. Fulfilling these commitments requires systematic modernization of the thermal power sector through the introduction of energy-efficient technologies, the integration of renewable sources, and the implementation of digital management systems. These steps can significantly reduce specific emissions even within the existing fuel structure.

The national energy transition must balance ecological and economic priorities. On one hand, stable electricity generation is essential for industrial growth and social well-being; on the other, the

sector's transformation is indispensable for meeting global sustainability standards. Modernization efforts should therefore combine technical upgrading - improving turbine and boiler efficiency, deploying waste-heat recovery, and introducing cogeneration schemes - with organizational and regulatory measures that stimulate investment in cleaner production.

The objective of this research is to assess the carbon footprint of Kazakhstan's thermal power plants, identify the principal factors influencing its scale, and propose effective technological solutions that ensure emission reduction without compromising the reliability of energy supply. The study employs internationally recognized methodologies for greenhouse gas accounting (GHG Protocol and ISO 14064) and draws on national statistical and regulatory data. Its findings are intended to support evidence-based policy decisions for the modernization of Kazakhstan's power sector and contribute to the country's progress toward a low-carbon economy [1].

2 MATERIALS AND METHODS

As the primary basis for this study, official statistical materials of the Ministry of Ecology and Natural Resources of the Republic of Kazakhstan [1], the Ministry of Energy of the Republic of Kazakhstan [2], as well as data from national and international reports on climate and energy [4]–[6], were used. The analysis employed methodological approaches regulated by international greenhouse gas accounting standards: the GHG Protocol (developed by WRI and WBCSD) and ISO 14064 [7].

3 RESULTS AND DISCUSSIONS

Kazakhstan, despite its relatively small population, is among the countries with the highest levels of greenhouse gas emissions per capita. In 2024, total emissions amounted to about 380 million tons of CO_2-equivalent, making Kazakhstan the largest emitter of greenhouse gases in Central Asia. The main contributors to emissions are the energy sector (around 80% of all emissions), industry, and transport [1]. A particularly significant share comes from thermal power plants that operate primarily on coal with high ash content and low calorific value. According to the Ministry of Energy of the Republic of Kazakhstan [2], electricity production in the country is carried out by 158 power plants, with 70% of total generation coming from coal-fired TPPs. The fuel balance is largely based on lignite and hard coal mined in the Karaganda and Pavlodar regions. Such dependence on carbon-intensive fuels predetermines the high level of greenhouse gas emissions, especially carbon dioxide (CO_2). According to the results of research conducted by scientists from Uzbekistan, the optimized design of a trench-type solar greenhouse makes it possible to reduce the specific heating load by 50% compared to the original design and decrease CO_2 emissions by 75% [3]. Excessive greenhouse gas emissions intensify the natural greenhouse effect, leading to global warming - a gradual increase in the Earth's average surface temperature.

The consequences of global climate change in Kazakhstan are becoming increasingly tangible. In recent decades, the country has experienced an increase in the average annual air temperature by 0.3–0.4 °C per decade [4], which is nearly twice the global rate; longer drought periods; reduced snow cover and glacier melting in mountainous regions; and a rise in extreme weather events, including droughts, dust storms, and sudden floods.

According to the National Climate Report [5] (prepared by the Ministry of Ecology of the Republic of Kazakhstan and Kazhydromet), if the current level of emissions is maintained, by the middle of the 21st century Kazakhstan may face a reduction of water resources by up to 30% in the southern regions; degradation of pastures and agricultural land; a decline in the yields of major crops; and an increase in the frequency of power supply disruptions due to rising summer temperatures and growing loads on energy networks. Thus, the impact of greenhouse gas emissions is not limited to the environmental dimension - it directly affects the country's economic resilience, as well as its food and energy security. Under these conditions, reducing emissions, particularly in the energy sector, becomes not only an international obligation but also an internal necessity.

Kazakhstan, as a full participant in the global climate process, signed and ratified the Paris Agreement in 2016 [6], thereby confirming its readiness to contribute to limiting global warming. In accordance with the provisions of the agreement, each country develops and submits so-called nationally determined contributions (NDCs) - voluntarily declared targets for reducing greenhouse gas emissions. In its updated NDC, Kazakhstan has committed to: reducing net greenhouse gas emissions by 15% by 2030 compared to 1990 levels (unconditional target); and up to 25% subject to external support (conditional target). These

commitments cover all sectors of the economy, including energy, industry, transport, agriculture, and waste.

The main source of emissions in Kazakhstan is the energy sector (≈ 79.9% of total GHG). Overall CO_2 emissions show three key phases: 1990–1999 - a sharp decline of almost 50% due to the collapse of the USSR and industrial downturn (minimum ~116 Mt CO_2 in 1999). 2000–2013 - economic recovery and rising emissions, peaking in 2013 (~263 Mt CO_2). 2014–2019 - stabilization and a slight decrease at a high level (~200–250 Mt CO_2). 2020–2023 - a temporary drop in 2020 (COVID-19), followed by gradual recovery by 2023. 2024 - official data have not yet been published; according to global estimates, the trend is upward again.

Kazakhstan's total gross greenhouse gas emissions average 348.844 million tons of CO_2-eq per year [1]. The dynamics of carbon dioxide emissions in Kazakhstan for 1990–2024, thousand tons of CO_2, are shown in Figure 1.

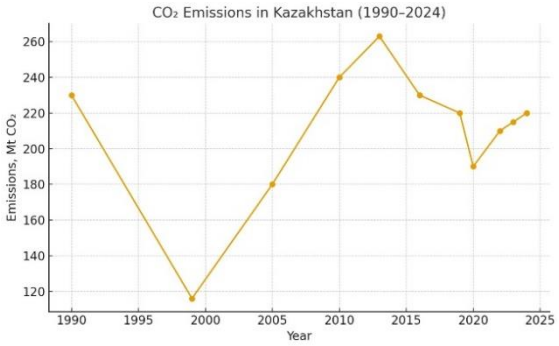


Figure 1: Dynamics of carbon dioxide emissions in Kazakhstan, 1990–2024, thousand tons of CO_2.

The carbon footprint of thermal power plants (TPPs) represents the total volume of greenhouse gas emissions, expressed in CO_2-equivalent, generated in the process of electricity production. In the context of growing attention to sustainable development and climate responsibility, this indicator has become a key criterion for assessing the environmental efficiency of energy facilities.

At present, various standards for greenhouse gas accounting have been developed, but the fundamental ones are the GHG Protocol and the ISO 14064 standard [7]. The GHG Protocol was developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). It provides guidance on how to properly structure emission sources and clarify what is included or excluded in the assessment. The protocol recognizes a methodology for calculating emissions across three categories:

- Scope 1 – direct emissions under the direct control of an organization. These typically include process emissions, stationary fuel combustion, mobile fuel combustion, fugitive emissions, etc.;
- Scope 2 – indirect energy emissions (purchased electricity, heat, steam);
- Scope 3 – other indirect emissions that result from an organization's activities but occur from sources owned or controlled by other entities [8].

Greenhouse gas emissions under Scope 1 can be determined either by calculation or by instrumental measurement, although the calculation method is most commonly used. In this case, actual organizational data on fuel consumption are combined with greenhouse gas emission factors for different fuels and processes.

A general formula for the calculation is:

CO_2-eq emissions (kg) = Consumption × Emission factor

Each type of activity has its own emission factor (EF), which indicates how much CO_2-equivalent is released when using 1 unit of a resource.

Let us give an example of a Scope 1 emissions calculation for a coal-fired combined heat and power plant (CHP). For instance, the annual consumption of hard coal is 100,000 tons; the lower heating value is 25 MJ/kg; the carbon content of the fuel is 60%; and the carbon oxidation factor is 0.98 (i.e., 98% of the carbon is oxidized to CO_2).

Step 1. Determining the mass of carbon in the fuel:

$$M_C = M_{fuel} \cdot C_{content} \quad (1)$$

Step 2. Considering the carbon oxidation factor:

$$M_{C,ox} = M_C \cdot O_{factor} \quad (2)$$

Step 3. Conversion to CO_2 (each 1 kg of C gives CO_2):

$$M_{CO_2} = M_{C,ox} \cdot \frac{44}{12} \quad (3)$$

The presented calculation example shows that, with known values of fuel consumption, carbon content, and the carbon oxidation factor, it is possible to accurately determine the mass of CO_2 emitted [9].

The methodology is based on simple stoichiometric relationships and is the standard for accounting direct Scope 1 emissions in the energy sector. It makes it possible to: link the

physicochemical characteristics of fuel with actual emissions; take into account incomplete combustion of carbon through the oxidation factor; provide a reliable basis for reporting under international standards (GHG Protocol, ISO 14064) [10].

Thus, even a simplified calculation clearly demonstrates how strongly coal-based power generation influences the carbon footprint of the energy sector and why this sector is the key source of emissions in Kazakhstan. For example, a CHP plant burning 100,000 tons of hard coal annually emits approximately 215,764 tons of CO_2 per year under Scope 1 [9]-[13].

Reducing the carbon footprint of thermal power plants is a key priority in Kazakhstan's energy decarbonization strategy. The introduction of energy-efficient technologies, the digitalization of generation management, the transition to cleaner fuels, and equipment modernization make it possible to achieve a sustainable balance between the country's energy needs and environmental protection goals [14].

For effective CO_2 reduction in Kazakhstan, it is necessary to consider the technical condition of thermal power plants (TPPs), evaluate modernization potential, analyze the experience of other countries in the region, and stimulate private sector involvement. The average age of TPPs in Kazakhstan is 61 years, with about 76% of them operating for more than 50 years. The average wear of equipment reaches 66%, and in some cities such as Oral, Stepnogorsk, Taraz, Kyzylorda, and Kentau, this figure exceeds 80% [9].

The transition to low-carbon energy is impossible without comprehensive modernization of thermal power plants, especially given their dominant role in Kazakhstan's power system. The implementation of energy-efficient technologies at existing TPPs makes it possible to significantly reduce specific greenhouse gas emissions without a fundamental change in the fuel base, which is particularly relevant in conditions of high dependence on coal [15].

Several key areas of energy-efficient modernization of TPPs in Kazakhstan can be highlighted:

1) Improving the thermal efficiency of power equipment. Most Kazakhstani TPPs were built during the Soviet period, and today their efficiency often does not exceed 30–35%. An increase in efficiency by even 2–3% can lead to a significant reduction in specific CO_2 emissions. This can be achieved by: replacing or modernizing turbines and boilers; optimizing the operation of regenerative heaters; improving thermal insulation of pipelines and elements of thermal circuits; and applying intelligent control systems for operating modes [16].
2) Implementation of low-grade heat recovery systems. Waste heat recovery from flue gases, the use of waste heat boilers, and the introduction of cogeneration schemes (combined production of heat and electricity) improve the energy efficiency of units.
3) Replacement and automation of auxiliary equipment.** The introduction of variable-frequency drives for pumps, draft fans, and blowers reduces auxiliary electricity consumption, which at old TPPs can reach 8–10% of generation. Transitioning to high-efficiency pumping units and ventilation control systems saves fuel and reduces emissions [17].
4) Intelligent control and monitoring systems. Modern digital solutions, such as automatic combustion control (ACC) systems, allow real-time optimization of the fuel combustion process, reducing overconsumption and emissions.
5) Conversion of boiler units to cleaner fuels. Switching from coal to natural gas in regions with available infrastructure makes it possible to cut the specific carbon footprint nearly in half [18].

4 CONCLUSIONS

Kazakhstan remains one of the largest greenhouse gas emitters in Central Asia despite its relatively small population, due to the country's high dependence on coal-fired thermal power plants. This structure of the fuel balance not only results in a significant carbon footprint but also exacerbates climate risks, including rising temperatures, reduced water resources, and land degradation [18].

Fulfilling the commitments under the Paris Agreement requires comprehensive measures, with the modernization of thermal power plants (TPPs) playing a central role. Increasing the thermal efficiency of equipment, implementing cogeneration and heat recovery systems, digitalizing combustion processes, switching to natural gas, and adopting energy-efficient equipment can significantly reduce specific CO_2 emissions even without a complete phase-out of coal.

However, the long-term sustainability of the energy sector is possible only through a gradual transition to renewable energy sources and the attraction of international investments and technologies. An important condition for the

successful implementation of the energy transition is the consideration of social impacts and the training of personnel for the emerging low-carbon economy.

Thus, the modernization of thermal power plants is not only an environmental but also a strategic economic necessity, ensuring Kazakhstan's energy and climate security.

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IT-Based Comparative Assessment of Renewable Energy Technologies Using Digital Monitoring and Data Analytics

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Keywords: Renewable Energy, Solar Energy, Wind Energy, Hydropower, Geothermal Energy, Bioenergy, Technical Performance, Economic Efficiency, Environmental Impact, Sustainable Development, Energy Technologies, Comparative Analysis, Energy Innovation, Energy Policy.

Abstract: This paper presents an IT-based comparative assessment of major renewable energy technologies, including solar, wind, hydropower, geothermal, and bioenergy, using digital monitoring tools and data analytics. The study integrates official statistical reports, peer-reviewed publications, and international energy databases for the period 2021–2024, with limited projections for 2025, to evaluate technical performance, economic efficiency, and environmental impact. Particular attention is given to the role of intelligent monitoring, levelized cost of electricity analysis, and data-driven modelling in improving the reliability and scalability of renewable energy systems. The results indicate that solar and wind technologies achieved the most significant progress due to higher conversion efficiency, declining generation costs, and rapid deployment. Hydropower remains one of the most technically efficient renewable sources, while geothermal and bioenergy continue to play important regional roles despite slower expansion. Environmental analysis confirms that broader renewable energy adoption contributes to lower life-cycle carbon emissions than fossil-based generation. The study also shows that hybrid energy systems, storage technologies, and smart-grid integration are essential for improving system flexibility and long-term sustainability. These findings support evidence-based planning and policy development for the transition to low-carbon energy systems.

1 INTRODUCTION

1.1 Global Trends in the Development of Renewable Energy Sources (RES)

Between 2021 and 2025, the global renewable energy market demonstrated steady growth, driven by technological innovation, declining equipment costs, and strengthened governmental support. According to reports from the International Energy Agency (IEA) and the Uzbekistan Green Economy Strategy, the installed capacity of renewable energy sources reached 2,800 GW by the end of 2024, exceeding the 2021 level by approximately 15–20% [1].

The development of global renewable energy capacity over 2021–2024 is presented in Figure 1. The curve demonstrates a year-on-year increase, with cumulative installed capacity growing from approximately 2,370 GW in 2021 to nearly 2,800 GW at the end of 2024. This expansion was primarily due to extensive new installations of solar PV and offshore wind, which together accounted for the majority of new capacity [2]. The trend also reflects a gradual phaseout of coal, driven by a combination of

falling equipment costs, government incentives, and increasing efficiency from new technologies.

Figure 1 highlights the strategic importance of solar and wind energy, as they have led market growth at an accelerated pace. The year-on-year increase reflects rising investor confidence and international policy measures supporting decarbonization. Overall, these findings indicate that renewable energy is increasingly becoming a fundamental part of the global electricity system, with little sign of slowing [3].

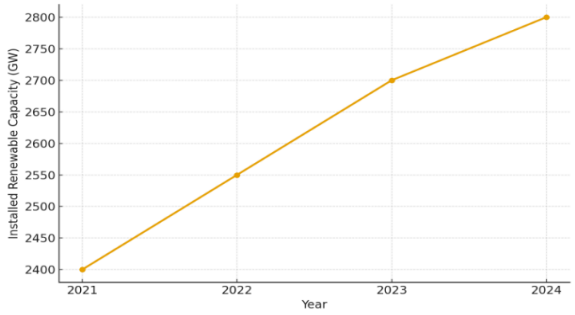


Figure 1: Growth of installed renewable energy capacity by year (2021-2024).

1.2 Technological Achievements and Innovations (2021-2025)

1.2.1 Solar Energy

By 2024, the average cost of photovoltaic (PV) modules had declined to $0.02–0.03 per kWh, making solar power competitive with traditional energy sources in several regions. The introduction of perovskite solar cells, achieving efficiencies of 25% and higher, emerged as one of the most significant research directions [4].

1.2.2 Wind Energy

The development and deployment of large-scale offshore wind farms reached new milestones. In 2024, more than 25 GW of offshore wind capacity was commissioned globally, an increase of 30% compared to 2021. Innovations such as vertical-axis wind turbines and larger rotor blades improved efficiency and reduced the levelized cost of electricity.

1.2.3 Hydropower and Pumped Storage

Hydropower continues to be a stable source of renewable electricity. Recent projects, however, have focused on small and medium-sized hydropower plants and pumped storage hydropower systems (PSH). Between 2022 and 2024, several projects enabled large-scale energy storage using water reservoirs [2].

1.2.4 Geothermal and Bioenergy

Geothermal heating and power generation technologies are increasingly deployed in regions with favorable geological conditions. Between 2023 and 2024, the number of geothermal power plants expanded significantly, particularly in the United States, Iceland, and Turkey. Bioenergy also continues to develop, though its expansion is regionally variable due to resource availability.

1.3 Economic Indicators and Declining Technology Costs

Over the past four years, the cost of electricity generated from RES has decreased substantially. In 2021, the average price of solar electricity was approximately $0.03–0.05 per kWh, dropping to $0.02–0.025 by 2024. Wind energy costs also declined from $0.04–0.06 per kWh in 2021 to $0.035–0.045 per kWh by 2024.

According to IEA forecasts, by 2025 the cost of solar energy may decline further to $0.015–0.02 per kWh, while wind energy is expected to reach $0.03–0.04 per kWh. These reductions will enhance the competitiveness of RES relative to fossil fuels across many regions.

Table 1: Current and projected costs of electricity from renewable energy (2021-2025).

Technology	2021	2024	2025 (Projection)
Solar PV	$0.03-0.05	$0.02-0.025	$0.015-0.02
Wind	$0.04-0.06	$0.035-0.045	$0.03-0.04
Hydropower	$0.02-0.05	-	-
Geothermal	$0.05-0.08	-	-

Table 1 demonstrates a consistent decline in solar and wind costs. Solar PV fell from $0.03–0.05/kWh in 2021 to $0.02–0.025/kWh in 2024, with a further projected decline to $0.015–0.02/kWh by 2025. Wind power costs similarly decreased, with reductions of approximately 8% over the last few years and a total reduction exceeding 20% since 2021 (AEO2013). Hydropower and geothermal costs remained relatively stable, indicating that solar and wind technologies are currently the most dynamic from a cost-competitive perspective. This is due to rapid

technological development, economies of scale, and favorable market conditions.

1.4 Environmental Achievements

By 2025, the widespread deployment of RES contributed to a 4–5% reduction in global CO_2 emissions compared with 2021 levels. The expansion of solar and wind energy enabled the displacement of a substantial share of coal- and gas-fired power plants.

Environmental challenges associated with large hydropower projects and wind farms remain pressing. Ongoing research focuses on mitigating ecological impacts while supporting the growth of renewable capacity.

Figure 2 presents life-cycle CO_2 emissions of various energy sources between 2021 and 2025. Fossil-fuel technologies, particularly coal and natural gas, remain the most carbon-intensive, while renewable sources such as solar PV, wind, hydropower, geothermal, and bioenergy exhibit much lower emissions levels (50–200 t-CO_2/MW installed), approaching zero in some cases. Solar and wind demonstrate the steepest decreases, driven by technological improvements, efficiency gains, and economies of scale.

The figure also underscores the growing environmental benefits of renewables in global decarbonization efforts. While bioenergy and geothermal have higher CO_2 footprints than other renewables, they remain far below fossil-fuel emissions. Declining renewable costs further reflect cleaner production methods, improved materials, and tighter environmental standards.

In summary, between 2021 and 2025, renewable energy technologies achieved substantial progress in efficiency, cost reduction, and environmental mitigation. Current trends indicate continued expansion and integration of RES into the global energy system, fully aligned with sustainable development objectives and international climate agendas.

2 MATERIALS AND METHODS

To conduct the comparative assessment of renewable energy (RE) technologies, we employed an integrated methodology encompassing data collection, systematization and processing, as well as modeling and statistical analysis. The primary objective is to determine the technical, economic, and environmental performance indicators of different RE types and to identify their advantages and limitations. This section details the methods, models, tools, and data sources used, together with the principles guiding their application.

2.1 Data Collection and Systematization

Up-to-date data across RE technologies were obtained from official reports of international organizations, scholarly publications, databases, and statistical agencies. The principal sources include:

- International Energy Agency (IEA);
- Global Wind Energy Council (GWEC);
- International Solar Energy Association (ISEA);
- Bloomberg New Energy Finance (BNEF) databases;
- Peer-reviewed journals indexed in Scopus and Web of Science.

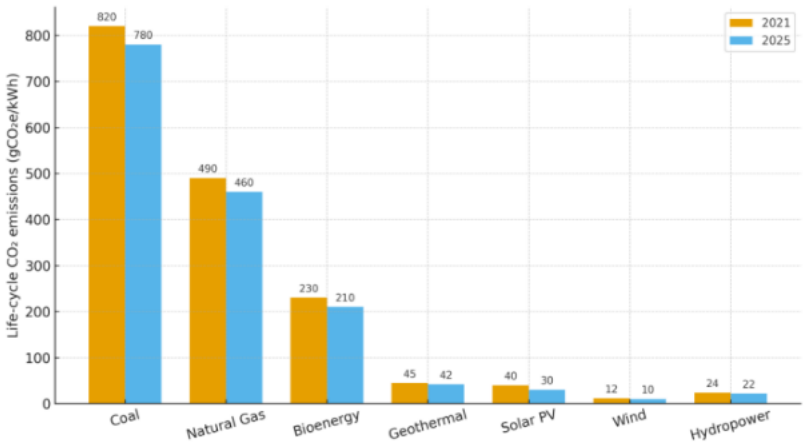


Figure 2: Comparison of CO_2 emissions by energy source (2021-2025).

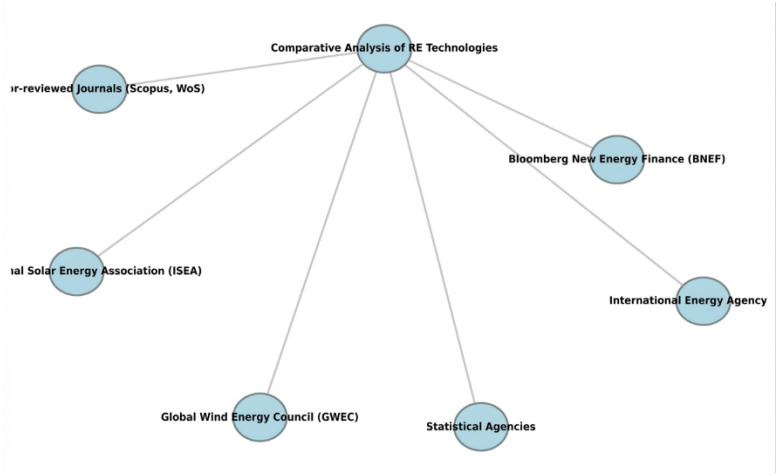


Figure 3: Map of data sources and their roles in the study.

Data collection methods:

- Analysis of official reports. Annual IEA, GWEC, and ISEA reports for 2021-2024 were used, covering global and regional volumes, costs, efficiencies, and environmental indicators of RE;
- Processing of statistical data. Dynamics of cost and efficiency were evaluated using statistical tools, including means, medians, trend analysis, and correlation analysis;
- Scholarly analytics. Reviews and meta-analyses of research articles were used to assess innovation trajectories and emerging technologies.

Figure 3 - Sources of data on different renewable energy technologies used as the basis for comparison in this study. The diagram indicates the inclusion of formal international reports (IEA, GWEC, ISEA) and industry specific databases (Bloomberg New Energy Finance - BNEF), as well as peer-reviewed scientific articles indexed in Scopus and Web of Science. Also statistical offices are represented as complementary sources of national and regional information. All these sources provide composite information about technical, economic and environmental implications of renewable energy, which would guarantee the research's completeness.

The diagram highlights the inter-dependency of data collection, with a multitude of inputs merging to create a consolidated analysis model. By tracing the information flow from various sources to the comparative analysis, the diagram demonstrates how reliability and accuracy are strengthened by triangulation. This synthesised methodology makes our study more robust by reducing the possibility of biases and achieving a global view. As such, the map highlights the importance of integrated multi-disciplinary data to generate evidence-based findings which are applicable in both academic research and policy formulation with regard to energy.

2.3 Modeling and Evaluation of Technical Indicators

To compare the technical characteristics of RE technologies, we used a composite model based on the calculation of conversion efficiency, loss levels, operating expenditures, and grid-integration capability.

Equation (1) General technical performance indicator:

$$E_{tech} = \frac{P_{out}}{P_{costs}} \times \eta_{tech} \times R_{\text{resource}}, \quad (1)$$

Where (1)

- P_{out} - average generated power (kW);
- P_{costs} - total equipment and operating costs (USD);
- η_{tech} - system efficiency;
- $R_{resource}$ - resource potential (e.g., solar irradiation, wind resource).

This model jointly accounts for technical parameters and regional resource endowment.

To standardize different renewable energy systems, all the components of the technical indicators were normalized using min-max scaling. The parameters η_tech, P_out, and R_resource were derived from averaged multi-year datasets provided by manufacturers and international agencies. The weights for the components were not random choices: efficiency was given more influence owing to its direct impact on energy conversion performance and resource potential, on regional feasibility. Sensitivity analyses were also performed to confirm that variations in the specific weights among

parameters would not give rise to a significant disproportion in the technical performance index, ensuring robustness and avoiding indicator bias.

System durability and reliability were evaluated using reliability/availability methods, including Markov-type models and classical reliability analysis.

Equation (2) Probability of failure-free operation over period T:

$$R(T) = e^{-\lambda T} \quad (2)$$

Where (2) λ is the failure rate (inverse of mean time between failures). Parameters were derived from equipment failure statistics provided by manufacturers and major operators.

Table 2 presents failure statistics and reliability features of major renewable energy (RE) technologies for 2021-2024. PV modules have a typical expected life of ~25 years and an annual average failure rate of 0.5-1.2 failures×year−1, corresponding to a high reliability coefficient of 95-98% (19). The most frequent problem are the glass breaks, cell degradation and cable corrosion. Wind turbines, which have an operational life of 20-25 years, show a slightly higher failure frequency (0.8-2.0 failures per year) and reliability of by 90–95% due to blade erosion, hydraulic failures and electrical faults. Hydropower plants, additionally, manifest the highest reliability rates (0.3-0.8 per year), and have service lives of up to 50 years; however, casing and rotor wear represent ongoing problems.

Geothermal power plants have low to moderate availability, averaging 25-30 years life span and failure rates between 0.4 and 1.0 per year that are mainly attributable to scale formation, corrosion and well failure. Biogas and biomass facilities, with typical lifespans of 15-20 years, show the lowest maintenance reliability ranges (85-92%), attributable to high failure rates (1.0-2.5 failures per year) resulted by fouling, engine wear, and heat-exchanger failures. Overall, the table illustrates how much open space there is among RE technolo- gies in terms of performance and difficulty of maintenance, demonstrating the need for technology-specific enhancements and M&O strategies. These results underline that solar and hydro power systems present a good potential for long-term reliability, whereas both biomass and wind technologies need further developments to mitigate failure risks and protract in use.

2.4 Economic Assessment and Cost Modeling

The levelized cost of electricity (LCOE) was computed using capital and operating expenditures discounted at the chosen rate.

Equation (3):

$$LCOE = \frac{\sum_{t=1}^{N} \frac{C_t}{(1+r)^t}}{\sum_{t=1}^{N} \frac{E_t}{(1+r)^t}} \quad (3)$$

Where C_t is total cost in year t; Et is electricity generated in year t; r is the discount rate; and N is the system lifetime (years). Cost and performance inputs were sourced from BNEF reports and national statistics.

Because LCOE represents a long-term discounted cost metric, all cost inputs (Ct) were adjusted to constant 2024 USD values using inflation correction factors. Discount rates (r) were selected according to IEA recommendations for technology-neutral evaluations. The model incorporates uncertainty through Monte Carlo simulations, enabling a range-based interpretation of economic performance. This approach avoids over-simplification and ensures that cost comparisons among technologies reflect realistic variability in capital expenditures, operational expenditures, degradation rates, and capacity factors.

Potential cost-reduction and efficiency-improvement pathways were explored using Monte Carlo simulations incorporating uncertainties in cost parameters, technological indicators, and market conditions.

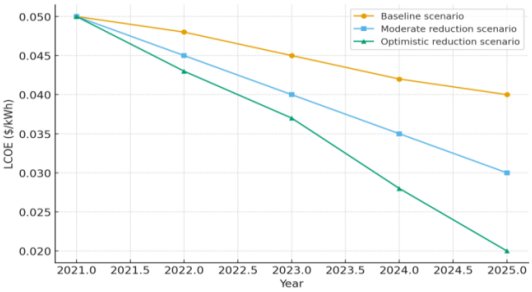


Figure 4: Scenario model of RE cost reduction (illustrative).

Figure 4 A model depicting possible RE cost decline pathways in the next half-decade (2021 to 2025). The figure details three scenarios: a 'business-as-usual' reference scenario, in which progress is only gradual, a moderate reduction scenario where technology evolves at a steady pace and an ambitious reduction scenario driven by nimble innovation and widespread market penetration. Baseline case shows linear reduction in the LCOE, whereas moderate and high cases are characterized by more steeper decrease reflecting innovation through improved efficiency, larger scale of manufacturing as well with energy storage integration.

This is an important reminder that the rate of cost decline depends on innovation and policy support. Under favourable conditions, renewables could

become significantly more competitive with fossil fuels much earlier than generally expected under an optimistic scenario that would disrupt international energy markets. Through the comparison of these pathways, the model demonstrates how uncertain forecasts are and underscores that targeted investments and supportive policies might provide significant benefits. Such a comparison highlights the strategic value of reinforcing the development of technology to increase the cost-effectiveness of RE systems.

2.5 Environmental Assessment

Environmental impacts were evaluated using an ecological-footprint/balance approach that compares greenhouse-gas emissions, natural-resource use, and biodiversity impacts.

Equation (4). Overall environmental index:

$$\text{Eco Index}=\alpha\times E_{CO2}+\beta\times R_{use}+\gamma\times B_{impact} \quad (4)$$

Where (4) ECO2 is life-cycle CO_2 emissions; Ruse is natural-resource consumption; Bimpact is biodiversity impact; and α, β, γ are weighting coefficients. Data were drawn from environmental studies, reports, and monitoring programs.

To construct the environmental index, all three sub-indicators (ECO_2, Ruse, Bimpact) were standardized using z-score normalization, as their physical units differ significantly. Weighting coefficients α, β, and γ were determined based on guidelines from UNEP and recent life-cycle assessment literature, assigning higher priority to life-cycle CO_2 emissions while still accounting for biodiversity and resource extraction impacts. Cross-validation using alternative weighting schemes (equal-weight, impact-proportional weight) revealed that final index rankings remained stable, confirming the robustness of the environmental evaluation.

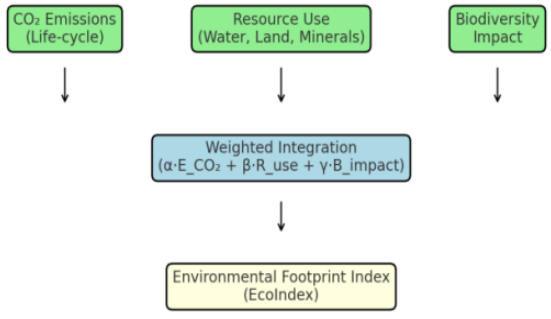


Figure 5: Schematic of the environmental-footprint assessment for RE technologies.

Figure 4 is an example scenario of RE (renewable energy) cost decline during the plan period (2021-2025). Figure 5 sketches three possible paths: a reference line of gradual improvements, a moderate reduction line which captures the steady pace of technological process, and an optimistic reduction where innovation is pursued more ambitiously and on a much broader front. There is a decreasing trend in the levelized cost of electricity (LCOE) for baseline but a faster reduction for moderate and optimistic, which are caused by improving efficiency, increasing scale of manufacturing as well as integration with energy storage.

This number highlights that innovation and policy support have an enormous effect on the rate of cost declines. The optimistic scenario suggests RE can indeed be very competitive with fossil fuels on large scale also under favorable conditions, and much earlier than what it was formerly supposed to become the case in a way that could deeply change energy markets across the world. Through the comparison of these pathways, it shows the dependence on future uncertainty in energy predictions and points out the benefits of directed investments and supporting regulatory measures. The relative visualization helps to identify the strategic need of fast technological development that breaches energy economics' welfare maximization toward designs for renewable energy systems.

2.6 Application of Machine Learning and Data Analytics

To analyze large datasets and forecast technology trajectories, we applied machine-learning (ML) methods, including:

- Regression models to quantify relationships between cost and efficiency;
- Cluster analysis to group regions by resource characteristics;
- Time-series models to forecast trends in costs and energy output. Analytical tools included Python (scikit-learn, TensorFlow) alongside R and MATLAB platforms.

The structure of the data analytics and machine learning (ML) system employed in this investigation for assessing RE technologies is depicted in Figure 6. The schema maps the various input sources (e.g., international energy reports, industry databases and scientific publications) through a preprocessing step where data is cleaned, normalized, integrated. These normalised dataset then* flows into ML modules using regression models, clustering algorithms and time-series prediction. The architecture follows a pipeline structure intended for processing large and heterogeneous datasets in order to develop actionable

insights about technical, economic and environmental indicators of performance.

Figure 6 illustrates the significance of Python and R as programming platforms that provide statistical modeling in addition to more advanced ML applications. Output of this system includes projections on efficiency improvement, cost reduction and environmental indicators which are then used for scenario analysis and policy assessment. The architecture is designed to be robust, transparent and adaptive since it includes different analytical layers which can be easily updated to support new data sets as well as methodological improvements. In sum, the diagram highlights the importance of leveraging both traditional statistical approaches and contemporary ML algorithms to improve reliability in renewable energy forecasting and strategic planning.

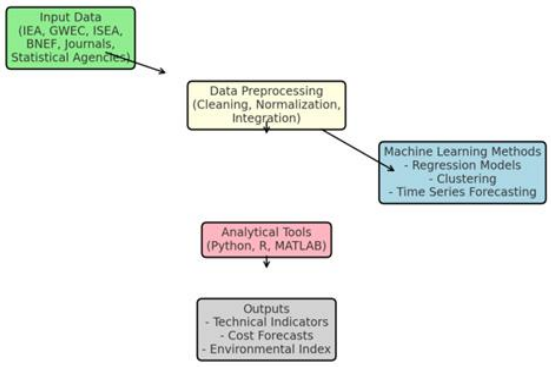


Figure 6: Architecture of the data analytics and ML system.

2.7 Model Verification and Validation

All models and methods were validated against historical datasets, with accuracy confirmed via cross-validation and testing on independent samples. Evaluation criteria included the coefficient of determination (R^2), root-mean-square error (RMSE), and mean absolute error (MAE).

Overall, the study adopts an interdisciplinary approach combining data collection/systematization with modeling of technical performance, economic indicators, and environmental impacts. This integrated framework enables an objective appraisal of the current state and development prospects of RE technologies and supports identification of optimal deployment strategies.

3 RESULTS OF THE RESEARCH

Based on the collected data, modeling, and analysis conducted in this study, the main results of comparing the technical, economic, and environmental indicators of renewable energy (RE) technologies are presented. This section examines the dynamics of technological development, system efficiency and reliability, as well as environmental performance. The results are structured into key domains, enabling conclusions to be drawn on both the current state and future directions of RE deployment.

3.1 Technical Performance and Efficiency of RE Systems (2021-2025)

Between 2021 and 2024, global installed RE capacity increased by 18%, reaching 2,800 GW by the end of 2024 (see Fig. 7). The fastest growth occurred in solar power and offshore wind farms.

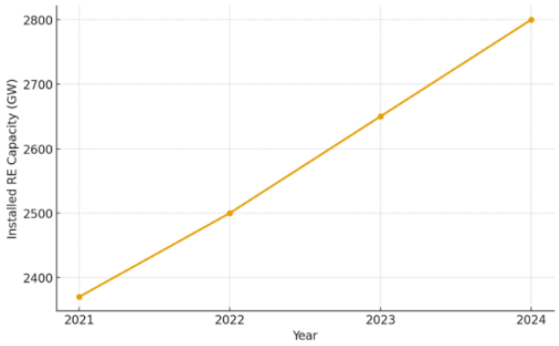


Figure 7: Growth of installed RE capacity by year (2021-2024).

Figure 7 provides a dynamic of installed renewable energy capacity through the course of 2021- 2024. A line chart indicates the increasing global capacity expanding from around 2,370 GW in 2021 to approximately 2,800 GW in 2024, which amounts to an 18% growth. The expansion occurs due to solar photovoltaics and offshore wind projects being deployed at a rapid rate underscored by technology cost falling and policy incentives being extended. The annual increase is enabled by technological advancements and the effort of the global community to fulfil the ambitious international commitments to reduce carbon footprint by means of clean energy. Another aspect highlighted by the whole graph is that RE is a robust segment of the global energy system that is expanding at a fast pace. The top renewables, solar PV and wind energy demonstrate the fastest expansion in terms of capacity additions, with other renewables have a steady growth rate. For instance, hydropower and geothermal do not contribute much to the growth but ensure the balance. Increased reliance of RE underscores the potential for sustainability to be achieved while ensuring energy security.

The conversion efficiency of solar panels rose to 25-26%, 2-3% higher than in 2021, driven by new materials such as perovskite photovoltaic cells. Wind turbines achieved efficiencies of 45-50% due to larger blades and advanced designs that improved output under comparable wind conditions.

Table 3 presents some of the main technical efficiency factors for key renewable energy (RE) technologies in 2024, according to recent reports and peer-reviewed studies. Solar photovoltaics reached conversion efficiencies of 25-26%, resource availability was approximately 2000-2200 kWh/m²/yr, with global installed capacity almost at 850 GW. Wind technology with improved hubs and rotors reached efficiencies of 45-50% with mean wind speeds of 7-8 m/s, resulting in a total capacity of 900 GW. The technical efficiency of hydropower is highest (85-90%), but resource potential varies strongly with location; about 450 GW are installed worldwide. Geothermal, however, had lower efficiencies in the 10-15% range due to geological limitations, but was present with 50 GW of capacity worldwide. Taken as a whole, these data emphasize the pronounced technology diversity: hydropower has remained the most technically efficient but wind and solar dominate when it comes to capacity expansion/tech scalabilities. The results indicate that a portfolio approach is critical to meeting sustainability and energy independence goals. Moreover, the table highlights that resource potential has a powerful impact on deployment styles and regional compatibility as an important dimension in technology acceptance.

Recent years have seen widespread deployment of innovations such as:

- Hybrid systems (solar wind): enhancing reliability and efficiency;
- Direct energy storage technologies: lithium-ion batteries with 90% round-trip efficiency, costs declining to $70/kWh by 2025 [5];
- AI-driven adaptive management systems: optimizing operational performance of RE plants [6].

Table 2: Failure statistics and reliability by RE technology (2021-2024).

RE technology	Average service life (years)	Average failure rate (failures/year)	Reliability coefficient, RRR (%)	Leading failure causes	Data source
Photovoltaic (PV) modules	25	0.5-1.2	95-98	Glass breakage, cell degradation, cable corrosion	Manufacturer reports, IEA [1]
Wind turbines	20-25	0.8-2.0	90-95	Blade wear, hydraulic failures, electrical equipment	GWEC, company reports [2]
Hydropower plants	30-50	0.3-0.8	97-99	Rotor wear, turbine damage, general equipment wear	Departmental reports, publications
Geothermal plants	25-30	0.4-1.0	93-97	Scaling, corrosion, well damage	Research studies
Biogas/biomass plants	15-20	1.0-2.5	85-92	Fouling, engine wear, heat-exchanger failures	Operator statistics

Table 3: Technical efficiency indicators of RE technologies (2024).

Technology	Efficiency (%)	Average resource potential	Average installed capacity, GW (2024)
Solar	25-26	2000-2200 kWh/m² per year	850
Wind	45-50	7-8 m/s	900
Hydropower	85-90	Site-specific	450
Geothermal	10-15	50-100 °C	50

Table 4: Failure statistics and reliability of RE equipment (2021-2024).

System type	Average service life (years)	Reliability coefficient (%)	Main failure causes
PV modules	25	97-98	Degradation, glass breakage
Wind turbines	20-25	92-95	Blade wear, hydraulic system issues
Hydropower plants	30-50	97-99	Rotor wear, turbine degradation
Geothermal plants	25	93-97	Scaling, corrosion

Figure 8 presents a map of innovative solutions and their regional adoption.

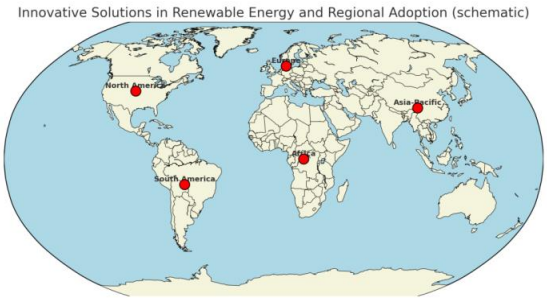


Figure 8: Map of innovative solutions and their regional adoption.

Table 3 summarizing selected major RE technology technical efficiency performance indicators up to 2024 from latest reports and peer-reviewed literature sources. Solar photovoltaic Conversion efficiencies from 2000 to 2200 kWh m−2 per year and a global installed capacity of around 850 GW. Wind power technology and its technology measures enabled by means of higher hub heights and larger rotor diameters were efficient at the 45-50% level for an average wind speed of 7-8 m/s, which was to be invoked with a total of 900 GW. Hydropower has shown to be the most technically efficient, with an efficiency between 85% and 90%, although it is also extremely location-dependent, currently generating about 450 GW worldwide. Geothermal, on the other hand had lower capacities of 10-15%, as dictated by geology (but still with global capacity of 50 GW). Taken all together, differences by technology that are striking for their magnitude emerge: hydropower still appear as the technically more efficient technology, followed in turn by solar and wind as far as capacity expansion or ability to scale are concerned. The Fair Consistent of both options highlight the beneficial contributions of a variety of RE technologies and thereby that system diversity is important in reaching sustainability and energy security goals. In addition, the table highlights that resource potential plays a major role in shaping deployment patterns; regional adjustements are key for the acceptance of technologies.

3.2 Reliability and Resilience of Equipment

Failure statistics for 2021-2024 reveal improvements in equipment reliability: solar modules now achieve 97-98% reliability, while wind turbines reach 92-95%. The main causes of failures include cell degradation (solar) and mechanical wear of blades and hydraulic systems (wind) [2].

Table 2 and 4 summarizes lost events and reliability statistics of selected RE technologies from the year 2021 to 2024. Photovoltaic (PV) modules are long-lasting with an average lifespan of 25 years, and a reliability level between 97 and 98%. There are basically two kinds of technical issue about PV modules, which is like cell degradation and glass breakage. Wind mills -with a service life of 20-25 years- have a slightly lower reliability (92-95%) since they are impacted by wear in the blades and failures in the hydraulic system. Figure 9 demonstrate that whereas, solar modules deliver consistent long-term performance, wind turbines require more rigorous maintenance strategies for upholding operational availablity.

However, the oldest HPPs built in Soviet times typically operate with up to 60% reliability compared to other stations and have a lifecycle of 30-50 years. However, they face problems of rotor abrasion and turbine damage. Reliability of the geothermal power plants is 90-97%, lifetime is 25 years, but there are frequent cases of failures due to scale and corrosion in the wells or equipment. On the whole, as indicated by the table above, majority of the RE technologies are highly technology matured; however, varying causes of failures give an impression on operational environments and maintenance performances. These insights highlight the importance of prioritised reliability science and engineering, including prevention of materials degradation for hydropower and PV technologies, as well as advancing innovation to control mechanical and chemical risks under wind and geothermal conditions.

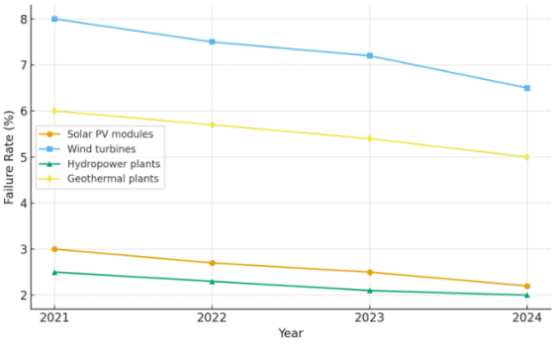


Figure 9: Dynamics of equipment failure rates by year.

The temporal variation of equipment failure rates for RE system between 2020 and 2024 is presented in Figure 9. The graphs show that annual failure rates are declining for all technologies, reflecting the progress made in design, materials and maintenance. For PV modules, the rate decreased from around 3.0% in 2021 to nearly 2.0% in 2024 and for wind turbines it decreased from 8.0% to roughly 6.5%

during this time of period. Hydro projects demonstrated low and steady failure rates, which slightly decreased from 2.5% to 2.0%. Geothermal dropped as well and I have an estimate for that at about 5.0% (had been 6.0%). These declining trends emphasize the technological maturation of RE systems.

It underscores that the gains in reliability were particularly strong for solar and wind technologies as improved component durability and better predictive maintenance systems are now visibly paying off. Great stability of performance, being essentially a very mature technology; the hydropower industry is not free from problems, but it has stood the test of time as far as its ability to consistently utilize water as an energy tool Geothermal: The geothermal power industry is heavily site-sensitive and many plants are suffering from long-term scaling and corrosion. Overall, the graph indicates that higher availability is an important consideration in reducing operational risks, in stimulating investor confidence and in making RE systems more deployable. It also highlights the importance of on-going surveillance and innovation in a bid to further minimise technical failures and lengthen equipment service life.

3.3 Economic Efficiency: Declining Electricity Costs (2021-2025)

Over the past four years, the cost of RE electricity production declined by 40-50%. In 2021, solar power averaged $0.03-0.05/kWh, but by 2024 dropped to $0.02-0.025/kWh. Wind power reached $0.035-0.045/kWh. Projections suggest further reductions by 2025, with solar reaching $0.015-0.02/kWh and wind $0.03-0.04/kWh.

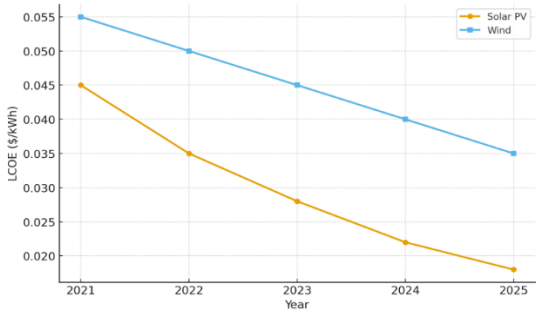


Figure 10: Dynamics of RE electricity costs by year.

Figure 10 shows development paths in the context of renewable energy (RE) electricity costs in the period 2021 to 2025, highlighting a continuing fall in the LCOE (levelised cost of electricity) for solar photovoltaics and wind power. Costs for solar power also fell dramatically (from $0.03-0.05/kWh in 2021 down to $0.02-0.025 in 2024, depending on location, and are projected to further decrease to $0.015-0.02 by 2025). Wind, also showed a similar trend with wind costs falling from $0.04-0.06 per kWh in 2021 to $0.035-0.045 in 2024 and expected to fall even further down to $0.03-0/4 by 2025. These trends can be explained by the increasing development and scale of technology as well as due to better generating and storage efficiencies.

The number also underlines how much more competitive RE is compared to fossil fuel power generation. With costs that are negating each other- and even falling below traditional sources of energy, solar and wind have a good potential to monopolize upcoming energy markets. The declining costs bolster the case for policy backdrops and investment themes that favor the acceleration of clean energy. Further, such a graph helps to visualise that RE is proven to be increasingly economical along with its enviromental advantages as an essential element of sustainable energy transitions throughout the world.

Table 5: Cost reduction trends (2021-2025).

Technology	2021	2024	2025 (Forecast)
Solar	$0.03-0.05	$0.02-0.025	$0.015-0.02
Wind	$0.04-0.06	$0.035-0.045	$0.03-0.04

Table 5 shows the forecasted decline in costs between 2021 and 2025 for solar and wind, as reported by Bloomberg New Energy Finance (BNEF) and the International Energy Agency (IEA). The numbers show a steady decrease in the LCOE of both technologies. On the solar front, pricing fell from $0.03-0.05 per kWh in 2021 to $0.02-0.025 in 2024, with future projections as low as $0.015-0.02 by 2025. Likewise, the cost of wind power dropped from 0.04-0.06 $/kWh in 2021 to 0.035-0.045 elastic_kJ trusti in 2024, with estimates for that could be as low as 0.03-0.04 value_perday_KG yrindep_tm nebprt m2fsync tractabl_ymd353895. These price declines are the result of continued technological improvements, increases in size and productivity, and operational experience in the renewable energy industry.

The comparative figures prove it that both solar and wind are fast near approaching levels of cost parity with the traditional fossil fuel-based electricity generation in certain parts of the world. The decline underscores the central role of innovation, enabling policy environments and economies of scale in trimming costs. Around 2025, they are likely to be found as integral elements of global decarbonization and energy security policies. In summary, the table

underscores how falling prices are a major driver for making renewable energy adoption faster and meeting sustainable goals over time.

3.4 Environmental Results

Between 2021 and 2024, the global expansion of RE contributed to a 4-5% reduction in CO_2 emissions in the energy sector, according to IEA and environmental monitoring data [7].

Despite positive results, certain RE technologies pose ecological risks: hydropower can alter hydrological systems and fish migration; wind farms can endanger birds and bats; solar power has an ecological footprint linked to panel manufacturing.

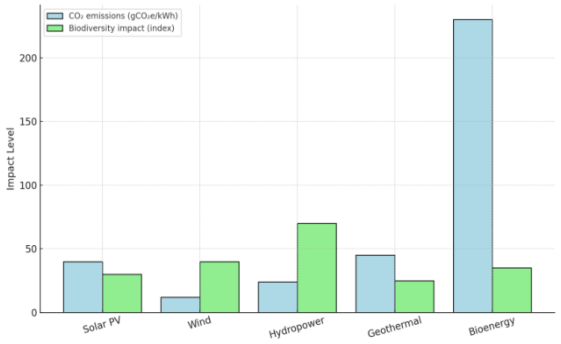


Figure 11: Comparison of ecological footprints of RE technologies: a) CO_2 emissions, b) biodiversity impacts.

A comparative study is also presented in Figure 11 for the ecological footprints of some RE technologies, with a special emphasis on: a) life-cycle CO_2 emissions; and b) biodiversity impacts (see Fig. 11). The results reveal that the carbon intensity of solar photovoltaic (PV) and wind energy is the lowest, and their life-cycle emissions are both less than 50 gCO_2e/kWh, which makes them very competitive from a decarbonization point of view. Hydropower also has relatively low carbon emissions, but represents higher impacts on biodiversity with ecosystem change and hydrological modification of rivers. Geothermal has moderate emissions as a policy analysis scalar and medium ecological pressure, while the highest carbon footprint of the bioenergy across all emission totals and significant environmental pressures (mainly land use, resource use).

The figures highlight the difficulty of assessing sustainability, for low emission technologies can still have environmental implications, such as those related to biodiversity. For instance, wind farms are almost carbon neutral but carry risk to bird and bat populations, while big hydroelectricity projects can throw off aquatic ecosystems. By illustrating these trade-offs, the figure illuminates that it is essential to take a multi-dimensional perspective on environmental assessment. This type of analysis gives a better basis for policy-makers and industry to prioritize those technologies that reduce both carbon and ecological perturbations, thus enabling a more balanced and sustainable transition towards the energy mix.

3.5 Forecasting and Development Scenarios

Machine-learning models were used to project RE technology development to 2030. Key findings include:

- Solar electricity costs will continue declining to \$0.01-0.015/kWh by 2030;
- Wind power will reach \$0.025-0.035/kWh;
- Energy storage deployment (batteries) will increase 2-3 times, enhancing stability and grid integration;
- Environmental impacts will decline through advanced materials and more efficient technologies.

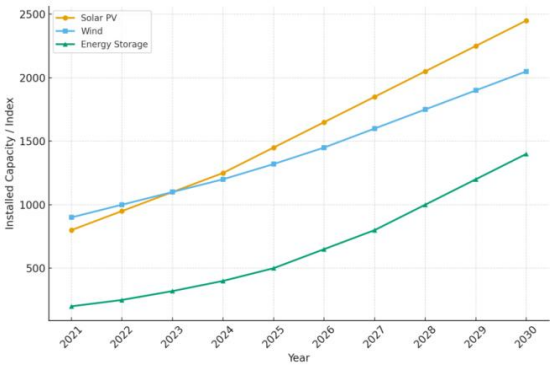


Figure 12: Scenario model of RE development to 2030.

A modelling scenario of 2030 RE technology progress on solar, wind and energy storage can be seen in Figure 12. The chart shows the inexorable rise in solar and wind capacities based on developments in technology and supportive policy structures. More than twice as much solar capacity is expected, compared with 2024 levels and wind will still be growing rapidly, including using offshore generation. Integration of large-scale storage stands out as one of the key elements, with capacity increasing by almost a factor of 3 by 2030, making power systems more flexible and stable.

The picture illustrates how the future of energy will look, transformed by innovation and investment. Swift cost declines, material innovations and the scaling up of hybrid systems all help “project more

optimistic growth trajectories" which see renewables meeting 50-60% of electricity demand in some parts of the world by 2030. At the same time, the model highlights uncertainies around market dynamics and infrastrcutre readiness which highlight how scenario planning is a necessary component of policy-making. In the end, the forecast points to the pace of renewable deployment as a critical part for reaching global decarbonisation and meeting international climate targets.

Recent years demonstrate substantial progress in RE technologies, including improved efficiency, reliability, and reduced electricity costs. Environmental indicators also show improvements, though further efforts are needed to minimize negative impacts. The integration of innovative solutions, storage systems, and hybrid installations will be central to scaling renewable energy in the coming decade.

4 DISCUSSION

Within the framework of the global energy transition, renewable energy (RE) is emerging as a cornerstone of energy system development across most countries. Analysis of recent data obtained in this study confirms that between 2021 and 2025 there has been significant progress in the technical, economic, and environmental indicators of RE technologies. However, despite these advances, several challenges remain concerning reliability, cost, environmental aspects, and integration into existing energy systems.

This chapter presents a comprehensive discussion of these dimensions, along with an evaluation of future development prospects and potential implementation scenarios for RE technologies in the modern context.

4.1 Technical Achievements and Their Significance

Between 2021 and 2024, the efficiency of both solar panels and wind turbines increased significantly due to the introduction of new materials (e.g., perovskite solar cells) and advanced design solutions.

The development of so-lar photovoltaic (PV) modules follows an exponential trend and Figure 13 shows the increase in efficiency with time from year 2021 to year 2024, which demonstrates that progress is happening very fast in the solar one converter system sector. These data suggest that average module efficiencies increased from about 22-23 % in 2021 to around 26% in 2024. This improvement is mainly due to the innovation of materials, for instance perovskite photovoltaic cells and approaches in production, like tandem-cell designs or better anti-reflective layers. The steady rise highlights the continued progress that solar industry has made in pushing conversion efficiencies upwards with little depletion of performance over time.

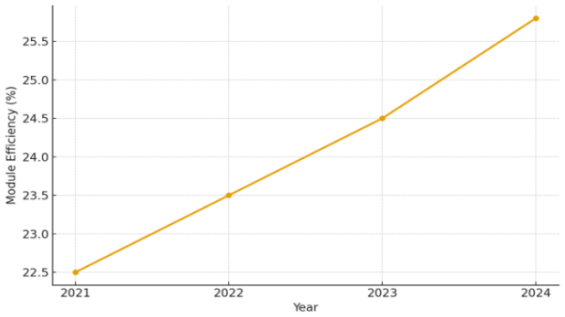


Figure 13: Efficiency growth of solar modules, 2021-2024.

The figure also highlights the strategic importance of these developments to the future deployment of global renewable energy. Higher module performance levels directly translate into lower levelized cost of electricity (LCOE) costs, improving the competitiveness of solar energy with traditional fossil fuels. Furthemore, the increase in efficiency enhances land-use effectiveness, further increasing electricity generation per unit area,-particularly important in population-dense or resource scarce locations. In conclusion, such a graph shows that like all technologies of the energy field progressive reductions in costs (ie a curve in a semi-logarithmic scale) accompany large-scale deployment of renewables within sustainable energy transitions.

This increase in efficiency contributed directly to reductions in the cost of electricity generation, with prices falling to $0.015-0.02/kWh by 2025.

The adoption of hybrid systems and energy-storage technologies enhanced supply stability, reduced energy losses, and supported performance under variable resource conditions [8]. For example, lithium-ion batteries with 90% round-trip efficiency and costs below $70/kWh now enable the development of autonomous and hybrid systems, which is particularly critical for remote regions.

Innovative solutions not only reduce the cost of electricity but also improve the overall reliability of energy systems.

Table 6 provides energy storage system performance, cost and reliability parameters in 2024 with a focus on lithium-ion and solid state batteries. Presently, lithium ion batteries are the dominant storage system with a rated efficiency of 9%, cost between $70 and$100 per kWh, and service life

between 10 to 15 years. These indicators confirm their level of technological development and cost, which consolidate them as the cornerstone for present large-scale integration of renewable energies. On the other hand, although still quite early in development, solid-state batteries (SSBs) have promising features with estimated efficiencies of about 95 %, expected costs below $50 per kWh by 2025 H2 as well as lifetimes superior to 15 years.

Table 6: Efficiency and reliability of energy storage systems, 2024.

System type	Efficiency (%)	Cost ($/kWh)	Avg. service life (years)
Lithium-ion batteries	90	$70-100	10-15
Solid-state batteries	95	< $50 (forecast 2025)	15+

The table highlights the groundbreaking nature of solid-state technology compared to traditional lithium-ion systems. When produced at scale, solid-state batteries have the potential to reduce cost and increase energy density as well as improve reliability and safety. Such an improvement would increase the reliability of renewable-rich power systems, and facilitate stronger penetration of intermittent sources like solar and wind. Together, the comparative data emphasize the fact that continued innovation and investment in storage technologies are crucial to accelerate the energy transition, improve grid resilience and achieve long-term sustainability goals.

4.2 Reliability and Environmental Aspects

In recent years, solar module reliability has risen to 97-98%, and wind turbine reliability to 92-95%. These figures reflect a high level of technological maturity and efficient maintenance practices [2].

Figure 14 shows the time dependences of FRs realisation for several type of RE equipment developed for years 2021-2024. The graph shows a tendency for decreasing failure rates overall, due to design improvements, use of more suitable materials and better predictive maintenance approach. The greatest reduction in failed modules were experienced by PV modules, dropping from approximately 3% in 2021 to slightly more than 2% in 2024. The wind power sector, though it still had far higher failure rates compared with other RE technologies, also showed significant improvements, from 8% to about 6.5%, during that time. There were persistent low failure rates for hydro and gradual decreases for geothermal facilities, associates with a better level of corrosion and scale control.

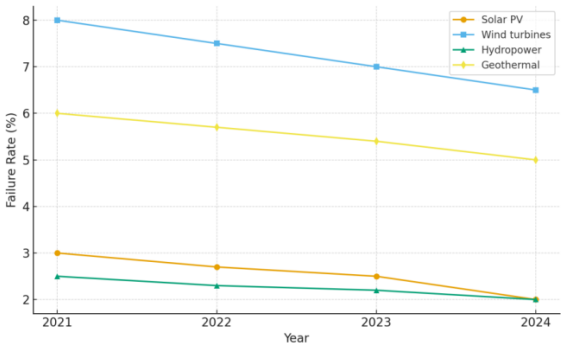


Figure 14: Dynamics of RE equipment failure rates, 2021-2024.

The number emphasizes the fact that focused technologies and better operating practices lead to higher system reliability. There have been, for example, improvements in the materials from which solar panels are fabricated or in the geometry and design of wind turbine blades or in the monitoring tools used at geothermal plants - all of which together is reducing downtime. They extend the service life of equipment, and decrease maintenance cost, as well as enhance investor confidence in RE projects. This general trend indicates that, as failure rates continue to decrease, renewable energy systems will increasingly be able to withstand system disturbances and be incorporated seamlessly into the global energy supply as robust and reliable components.

Despite clear advantages, RE technologies face ecological challenges linked to the production and disposal of solar panels and batteries.

Table 7: Environmental indicators of RE technologies, 2021-2024

Indicator	Value	Key challenges
CO_2 emissions (production)	20-50 g/kWh	Energy intensity and chemical use
Panel recycling	85-90% recyclability	Insufficient recycling infrastructure
Biodiversity impact	Low (if well-sited)	Bat and bird mortality near wind farms

Conclusion: While RE is substantially safer environmentally than fossil fuels, improvements in recycling and reductions in upstream ecological costs are required.

Table 7 presents the main environmental impacts attributed to RE technologies for the time-frame of 2021-2024. The life-cycle CO_2 emissions in the production phase is between 20 and 50 g/kWh which demonstrates a much more reduced value than that of fossil fuel generation. Nonetheless, this range highlights the energy-demanding nature of manufacturing and reliance on particular chemicals. Recyclability Another very important issue is the recyclability: till date, solar panels have an 85-90% recycling capacity, but in reality a large-scale machining infrastructure doesn't exist and it has been identified as one of the main bottlenecks. Moreover, although the effects on biodiversity are predominantly low in properly located sites, wind farms still have potential risks to bat and bird populations.

The table highlights that despite the substantial environmental advantages of RE technologies in comparison to traditional sources of energy, several challenges remain. In any case, achieving emissions reductions in manufacturing depends on the deployment of low-carbon supply chain and cleaner production pathways, while developing recycling infrastructure will be essential to the effective management of end-of-life solar panels and batteries. In addition, conservative spatial management and mitigation measures (e.g., wildlife monitoring and adaptive turbine operation) are required to ensure that biodiversity risk is kept at a minimum. Together, they highlight the need for an integrated approach to sustainability based on carbon reduction together with wider environmental perspectives.

4.3 Economic Aspects and Development Scenarios

Due to technological advances and production scale-up, RE electricity costs decreased by 40-50% between 2021 and 2024.

Table 8: Electricity costs from RE, 2021-2025.

Year	Solar ($/kWh)	Wind ($/kWh)
2021	0.03-0.05	0.04-0.06
2024	0.02-0.025	0.035-0.045
2025 (proj.)	0.015-0.02	0.03-0.04

Economic performance now rivals that of conventional energy sources, opening wide prospects for scaling up RE deployment.

The trajectory of electricity cost from (RE)-solar photovoltaic and wind technologies-are described in Table 8, for the period 2021-2025. The numbers show a clearly descending curve, as it went from the $0.03-0.05 per kWh range in 2021 to $0.02-0.025 in 2024 and even lower at projected $0.015-0.02 by 2025. WME, too, follows a comparable path: $0.04-0.06/kWe to $0.035-0.045/kWe in 2021 after which it is expected to fall further to the range of $0.03-0.04/kWe in 2025/6 [6]. Those declines are the result of hundreds of incremental improvements, expansion and increased efficiency in both generation and grid integration.

The table highlights the growing competitiveness of RE with fossil fuel-based electricity generation. The predicted price levels imply both wind and solar will not only become cheaper than coal, but that it will even be cheaper than gas and other fossil fuels in most of the world, challenging the conventional power supply with a new setup. These trends demonstrate the critical role supportive policies, international investments and ongoing innovation in storage and hybrids on affordability. In the end, the table shows that by 2025 RE will be one of the most competitive mechanisms for sustainable global energy transitions.

Modeling, including advanced scenarios with improved technology and storage capacity, suggests that by 2030 solar power will reach $0.01-0.015/kWh, and wind $0.025-0.035/kWh. Under such conditions, RE could provide 50-60% of national energy demand in several countries.

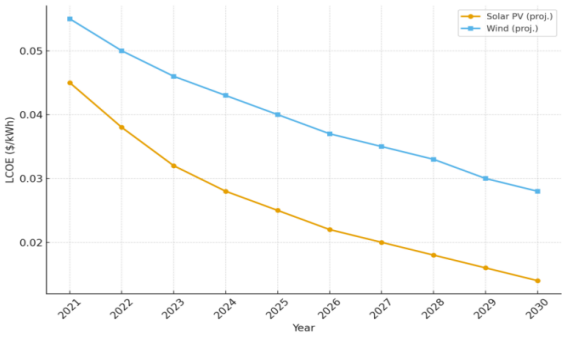


Figure 15: Projected scenarios of RE cost development to 2030.

Figure 15 presents future-oriented scenarios for the development of renewable energy (RE) technology costs for up to 2030, casting a special focus on solar photovoltaic and wind power technologies. The chart captures a steadily downward trajectory of leveling cost of electricity (LCOE) predicting that solar power will fall from roughly $0.045/kWh in 2021 to $0.014/kWh by 2030, and wind power should do likewise establishing from an

average level of $0.055/kWh in 2021 to about $0.028/kWh over the year range. These estimates include additional technological development and the impact of large-scale deployment, suggesting that renewables could further improve their competitiveness on both cost and potential degree of economic penetration across a range of sectors.

The figure suggests that in the most optimistic scenarios, solar and wind power have the potential to dunderpricistribute almost all fossil fuel-based electricity generation (somewhere among a combination of natural gas, coal, and oil) to be flipped down or off-but not over-into discount-ruled future energy lists. Moreover, these scenarios showcases the significance of technological innovation in storage solutions, grid integration and materials science - factors that should impact how fast costs come down. The many pathways in the chart highlight the range of the possible, both with respect to what could happen but also what other governments may be considering and thus needing to understand in their own decision process. At the same time, it underscores a key takeaway: that renewables are well-positioned crediтyro play a significant role in meeting global decarbonisation goal by 2030."

4.4 Impact on Energy Policy and Sustainable Development

The integration of RE technologies contributes directly to the UN Sustainable Development Goals (SDGs), including the reduction of greenhouse-gas emissions, development of innovation-driven economies, and decreased reliance on fossil fuels [9]. By 2030, expanding the share of RE could reduce global CO_2 emissions by 4-6%, thereby supporting compliance with the Paris Agreement.

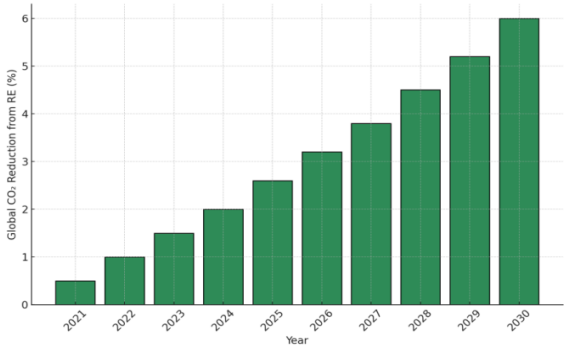


Figure 16: Impact of RE on global CO_2 reduction, 2021-2030.

The influence of renewable energy (RE) deployment on global CO_2 reduction from 2021 to 2030 is presented in Figure 16. From the graph, we confirmed that RE was gradually making more and more impact on emissions mitigation with reductions starting at 0.5% in 2021 to a target of about 6% by 2030. This progress is a result of continued rapid growth in solar and wind, modest improvements in geothermal and bioenergy, as well as sustained contributions from hydropower. It illustrated that amount of RE added to the national grid translated into quantifiable reductions in carbon emissions, highlighting the importance of RE technologies in climate action plans.

The diagram also makes it clear that, although decreases are gradual on an annual basis, the 2030 cumulative effect is large. A 6% worldwide reduction in CO_2 emissions due to RE technologies is very well articulated with the Paris Accord and UN SDG goals. What's more, the figure illustrates that regional and technological differences matter: countries that have been the most successful at deploying solar, wind and storage technologies are estimated to deliver the biggest reductions and others may be later than 2040 - the point at which these estimates end - because they're behind on clean infrastructure or resources to pay for it. In sum, the window reinforces the urgency to scale up RE investment and promote international cooperation in order capitalize its potential to decarbonize.

4.5 Limitations and Challenges

Despite progress, significant challenges remain:

- Underdeveloped infrastructure for energy storage and transmission [10];
- Uneven distribution of RE technologies, particularly across developing nations;
- Environmental risks associated with equipment recycling and disposal;
- High upfront capital costs of deployment.

These issues require systemic approaches, international collaboration, and sustained investment in research and innovation.

5 CONCLUSIONS

This study conducted a comprehensive analysis of modern renewable energy (RE) technologies for the period 2021–2025, focusing on their technical, economic, and environmental performance. Based on the collected data, modeling, and comparative analysis, the following key conclusions can be drawn:

1) Significant improvements in efficiency and reliability have been achieved across RE systems. Solar energy has demonstrated the most rapid progress, primarily due to the

adoption of advanced materials such as perovskite solar cells. Wind energy development has been driven by larger and more efficient turbine designs. In addition, the integration of hybrid systems and energy storage solutions has enhanced system stability and operational flexibility, which are essential for large-scale deployment [8].

2) The cost of electricity generated from renewable sources decreased substantially during the study period, making RE increasingly competitive with conventional energy. Projections indicate that by 2030, the cost of solar electricity may decline to $0.01–0.015/kWh, while wind energy could reach $0.025–0.035/kWh. These trends create favorable conditions for expanding the share of renewables in global energy systems.
3) Renewable energy technologies provide significant environmental benefits, particularly through the reduction of CO_2 emissions and decreased reliance on fossil fuels. However, several challenges remain, including the environmental impact of large-scale hydropower projects and the need for effective recycling and disposal of equipment. Despite these issues, the overall ecological footprint of RE remains substantially lower than that of conventional energy sources.
4) The expansion of renewable energy is still constrained by several factors, including insufficient energy storage and transmission infrastructure, high upfront capital costs, and uneven distribution of technologies across regions. Addressing these limitations is essential to ensure balanced and sustainable growth of the sector [10].
5) Further progress in renewable energy deployment will depend on continued investment in research and development, particularly in advanced materials and energy storage technologies. In addition, improving grid integration, expanding recycling infrastructure, and strengthening international cooperation will play a crucial role in accelerating adoption and minimizing environmental risks [11].

In conclusion, the results of this study confirm that renewable energy is becoming a key component of the global energy system. Continued technological advancement, cost reductions, and the resolution of existing infrastructural and environmental challenges will provide the foundation for a large-scale transition to sustainable energy, contributing to climate change mitigation and long-term energy security.

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Intelligent Modelling of Wind Power Plant Potential for the Modernization of the Green Energy Sector

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Keywords: Wind Energy, Wind Resource Potential, Onshore Wind Power, Offshore Wind Power, Barriers, Environmental Aspects, Technology, Sustainable Development.

Abstract: This paper provides a complete comparison of the potentiality of onshore and offshore wind power plants considering technical, economical, environmental and geographical aspects. The application uses multiple data analysis tools such as long-term meteorological patterns, wind flow models, GIS for spatial mapping of wind resources, and LCOE technique for economic assessment. Such approaches would allow for defensible assessments of regional wind potential, as well as the constraints on large penetration levels. The study analyses the distribution of wind resources, turbine performance characteristics, land use, offshore risks to environment and operational reliability in various climatic locations. The results show that offshore wind farms have better and more stable wind resources than onshore farms, since they obtain higher capacity factors (40-50%) than onshore ones (35-45%). Nevertheless, offshore installations involve higher capital costs and pose technical issues concerning corrosion installations in deep water, and reduced maintenance access. Onshore wind farms are still economically feasible since infrastructure (such as grid and roads) already exist and it has reduced construction costs however, the development of new sites is currently limited by population density as well as noise regulations amongst others. The research value of this study is that it has been the first to investigate windpower development from a complete meteorological, geographical, technical and economic perspective. The value added is seen in providing a framework to policymakers and investors for assessing the wind power potential and prioritizing of sites for installation. This examination emphasizes the role of innovative designs (floating) and technologies (advanced monitoring), and government intervened policies to promote cost reduction and risk limiting. In total, the study validates that wind energy is a strategic source of generation for sustainable development and accordingly offers boo-table paths on enhancing efficiency and environmental soundness in both onshore and offshore wind plants.

1 INTRODUCTION

In the context of the world economy, the finding of reliable and environmentally acceptable sources of both power and energy is of special relevance owing to climate change, the progressive increase in energy requirements, and limited reserves of conventional fossil resources. Wind energy plays an important role among renewable energy sources because it is one of the most environmentally friendly and promising sources. Wind power stations harness energy from moving air masses as electrical energy with minimized greenhouse gas emissions and environmental pollution [1].

1.1 Relevance of the Study

Global practice shows that the development of wind power helps diversify the energy balance and decrease reliance on hydrocarbons. The share of wind power in the world's electricity supply has been growing continuously over the past two decades

(International Renewable Energy Agency (IRENA). The global installed wind power capacity surpassed the 800 GW mark in 2022, remaining a fast-growing sector with large-scale technological development and investment [2], [3].

However, the development of wind power has been hampered by numerous technical, commercial, environmental/wildlife, and social obstacles. Therefore, a comparison between onshore and offshore wind systems is required to identify the most optimal and promising development directions.

1.2 Objectives and Research Tasks

This study aims to analyze onshore and offshore wind plants and the obstacles that hinder their global implementation from both the technical and economic perspectives. The following research objectives were set:

- Evaluate scientific and methodological approaches to quantify the potential of wind resources.
- Investigate the technical specifications, benefits, and limitations of onshore and offshore wind farms.
- Assess the economic and environmental implications of wind implementation.
- Determine critical challenges and recommend actions to address them.
- Compare the economic efficiency, environmental safety, and development prospects of the two types of wind power.

1.3 Literature Review and State of Research

A substantial amount of research has been conducted to address the global wind potential, onshore and offshore technology comparison for wind generation, and barriers limiting its development. The onshore wind potential worldwide strongly exceeds the actual electricity demand, especially in areas endowed with good wind conditions and topography and an already developed transmission grid [4]. However, the exploitation of onshore wind is limited by land use constraints, ecological concerns (including environmental protection), and more recently, growing social resistance in densely populated locations.

Offshore wind plants are receiving growing interest because the wind flow in the sea is stronger, less turbulent, and more stable than that on land. That offshore capacity factors are generally 5-10% higher than onshore and lead changes to increase the annual energy yield in a significant way [5]. In Europe (North Sea, Baltic Sea) and Asia (China, South Korea, and Japan), large field development programs have already been established, providing empirical evidence of the superior technical performance and long-term production stability of offshore installations [6].

However, offshore wind has its own lifetime challenges due to its very high capital costs compared with onshore wind: difficulty in installation, corrosion out of land, and maintenance under a severe marine environment are examples. The estimated costs of foundation installation, subsea cabling, and dedicated offshore maintenance vessels may contribute up to 40% of the overall project costs. Ecological concerns are also critical topics that need to be addressed through extensive environmental assessments (e.g., effects on marine environments, seabirds, and noise-sensitive species) [7].

In contrast, onshore wind farms benefit from developed infrastructure and face easier logistic access and cheaper construction and maintenance. Onshore wind is technically mature and widespread in global deployment; however, the potential for expansion is constrained by land availability, proximity to homes, noise limitations, visual impact restrictions, and the partitioning of suitable sites [8].

Recent reports (e.g., EWEA, IRENA, WWEA and GWEC [9]) point out that in order to move forward the development of wind energy at the next level, there are various gaps that need to be addressed.

- the importance of high-resolution wind resource modeling in complex terrain;
- interaction of wind forecasting with smart grid;
- rapid growing technology of floating offshore platforms which are designed for deep-water zones;
- enhanced environmental monitoring technologies;
- • Stronger economic drivers for lowering the LCOE for offshore.

In general, literature points towards a trend of increment in offshore wind development, which however has to face some economic, technical, and environmental challenges. In contrast, onshore wind has already become more mature and is being placed under growing spatial and social pressures, which means that a balanced site- and context-specific approach to future development needs to be sought.

1.4 Geographical Features and Resource Distribution

The geographical distribution of wind resources is a fundamental factor that determines the feasibility and long-term efficiency of wind energy deployment. Wind potential varies significantly across regions owing to differences in atmospheric circulation, terrain elevation, land-sea interactions, and climatic regimes. According to the EWEA and Global Wind Atlas datasets, onshore wind resources are generally most abundant in areas characterized by pronounced stratification and meteorological gradients, such as wide plains, elevated mountain passes, and continental coastlines [8].

In contrast, offshore wind resources are concentrated in coastal zones, continental shelves, and open seas, where large-scale atmospheric dynamics generate stronger, more stable, and less turbulent wind flow. Offshore regions typically exhibit average wind speeds 20-40% higher than comparable onshore territories, leading to higher capacity factors and improved energy yield consistency.

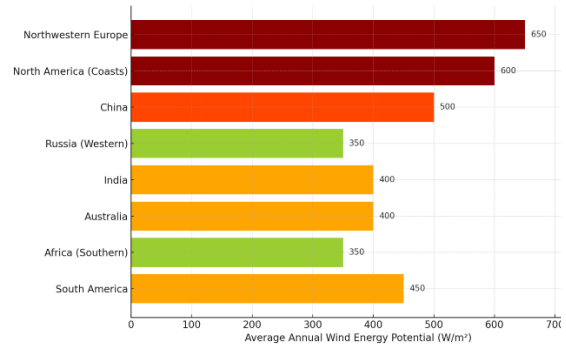


Figure 1: Average annual wind resource potential by global regions.

Figure 1 shows the average annual distribution of potential for regions across the globe. Among the best countries for wind power development are Northwestern Europe and the North Atlantic coastlines, the Pacific rim area of the United States, and other parts of Asia, including China, Japan, and Southeast Asia. In Northwest Europe, especially the United Kingdom, Denmark, Germany, and the Netherlands, the wind potential is 600-700 W/m², and these countries are global leaders in the deployment of offshore wind.

In Asia, China and India have vast potential above 300 W/m², which explains the high-speed deployment in these two countries owing to their large coastal areas and strong support from the government. The wind resources of the Russian Federation and Eastern Europe in general are intermediate between moderate (200-400 W/m²) resource levels and areas with high potential where land use conflicts may arise from competitive uses from growing populations but fire-sparsely populated coastal, steppe, and mountain zones.

Australia and South America have moderate to high wind resources, and many coasts and inland areas have the potential for utility-scale installations. These patterns suggest that wind resource abundance across the globe is characterized by both rich environmental constraints associated with peculiar sites, demanding regional-oriented planning targets to achieve optimal technical and economic feasibility.

In conclusion, geographical assessments unambiguously assert that the greatest long-term potential is apparent in areas with high atmospheric circulation and large coastal exposure. These further highlights how onshore and offshore wind deployment, if complemented by regional geography and climate, can add strategic value.

1.5 Methods of Wind Resource Potential Assessment

Estimation of wind resource potential must be performed based on a systematic methodological framework encompassing meteorological readings, geospatial analysis, and advanced atmospheric modelling. WRC campaigns generally start with the gathering of long-term meteorological data, such as wind speed, wind direction, air density, temperature, and atmospheric pressure. These data, including national meteorological stations, reanalysis products, and long-term climate archives, are the most important inputs for computing available wind energy at diverse heights and sites [10].

In addition to traditional ground-based measurements, satellite-derived data (e.g., Sentinel, MODIS) and automated observation sites have been used in recent years to produce high spatial-temporal resolution datasets. These facilities considerably improve the accuracy of propensity forecasts, particularly in remote areas where ground-based meteorological infrastructure is lacking. Measurements from lidar and sodar remote-sensing devices are also extensively used to capture vertical wind profiles, which are crucial for turbine hub-height estimation.

Temporal variability is a critical element in wind resource assessments. The energy production, fatigue loads on turbines, and general reliability of wind

power plants are directly influenced by seasonal and daily wind fluctuations, inter-annual variation, and extreme meteorological events. Thus, short- or long-term variability trends of the wind or weather profile have also been usually analyzed based on statistical analysis, such as Weibull probability distribution fitting [11], extreme value analysis (EVA) [12], and turbulence intensity assessment [13].

However, the precision of wind resource estimation has been further improved using advanced numerical atmospheric models. Mesoscale models, such as the Weather Research and Forecasting (WRF) model, are commonly used to simulate wind fields at a high spatial resolution, in which terrain effects, surface roughness, and atmospheric stability can be considered. Computational Fluid Dynamics (CFD) models can simulate detailed micro-scale flows in complex terrains, such as mountainous areas and coastal districts, where the wind field is extremely sensitive to topography.

Meteorological, satellite, and modeling-based methods can be used in combination to provide a strong and comprehensive characterization of wind resources. The use of these methods will allow for the reliable assessment of high-opportunity regions and appropriate turbine placement, providing a clear indication for developing efficient on-land wind systems or offshore development.

1.6 Technological Features of Onshore and Offshore Wind Power Plants

Onshore wind power plants are the most mature part of the global wind energy market, with relatively low construction and operation costs. They are advantageous because they are more accessible for decommissioning, easier to service, closer to existing electrical grids, and less complex in terms of logistics. In the case of onshore turbines, mature manufacturing standards and efficiency-optimized supply chains exist, which lead to fast deployment and low operational costs [11]. Onshore turbine technology has reached a high level of maturity with high reliability, standardized maintenance, and ease of integration into regional grid infrastructure.

Although offshore wind power plants require a substantially larger amount of investment, they present numerous technological and operative benefits. Offshore locations usually have stronger, steadier, and less turbulent wind flows, resulting in higher capacity factors and more consistent annual energy production. The lack of density of developments in marine areas negates land use conflicts and visual impacts, allowing large numbers and very high-rated turbines (10-15 MW and higher) to be deployed. These advances have also facilitated the emergence of next-generation offshore technologies, such as long-blade turbines, advanced floating platforms, and aerodynamic rotor optimization [12].

However, there are significant technological difficulties associated with offshore wind systems. There are threats in the rough marine environment, including corrosion, salinity, violent weather, and hydrodynamic loads. Wave and current loads and long-term fatigue stress need to be considered for foundations such as monopiles, jackets, and floaters. In addition, offshore maintenance requires special vessels, is dependent on the weather for access windows, and is costly to monitor remotely. The remote location of offshore sites requires the installation of subsea cables, offshore substations, and new grid connection concepts.

Although offshore wind technology offers vast potential for energy production, factors such as solving tough engineering problems, maintaining durable maintenance procedures, and employing the best fitting installation logistics are key to successful implementation. Onshore and offshore technologies have complementary roles in the global wind energy market, with technological advancements enhancing performance, reliability, and cost-effectiveness.

1.7 Barriers to Wind Energy Deployment

Although the potential for wind energy is considerable, several interrelated barriers limit its deployment at a utility scale. These obstacles are divided into technical, economic, environmental, and social issues, which play crucial roles in determining the viability and sustainability of wind energy projects.

Technological Obstacles: The Technological obstacles arise from the intermittency and variability of wind energy, as well as advanced storage methods and grid integration. The fluctuation of wind speed necessitates large-scale storage, grids, and forecasting technologies to achieve supply stability. Furthermore, turbine reliability remains an issue for offshore installations owing to the risk of corrosion, extreme weather, and high mechanical loads. Operational safety, component lifetime, and maintenance aspects remain important targets in technology research [13].

Economic: The high capital costs associated with wind energy projects, particularly offshore, are for initial investments in turbine design and

manufacturing, logistics, installation, and interconnection to the electric grid. The high costs of marine foundations, installation vessels, and subsea infrastructure, as well as long payback periods, often prevent investment. In several markets, the absence of predictable government support schemes (e.g., guarantees, feed-in tariffs, or tax breaks) means that financial attractiveness is significantly diminished. Market uncertainties and the volatility of electricity prices can also challenge long-term investment planning [14].

Environmental obstacles: Although wind energy is environmentally cleaner than fossil fuels, some environmental challenges must be overcome. Terrestrial installations can impact wildlife habitats, including bird and bat populations, whereas offshore wind farms can alter marine ecosystems, seabed features, noise profiles, and migration corridors. In marine areas, construction activities can disturb benthic habitats and fish spawning sites. Additionally, turbines and support structures would be visible in coastal and mountain environments, and changes to the landscape will occur, mandating thorough environmental impact studies, including appropriate mitigation [15] - [17].

Social obstacles: High importance of social acceptance for achieving success with wind power in general. Public resistance frequently involves issues of visual impact, noise, zoning and land use, depreciation of real estate values, and allegations of health risks. The lack of knowledge about the environmental and economic benefits of wind power results in community resistance to project development, site permitting, and construction. Coastal residents, tourism sectors, and fishing communities might offset offshore projects as well. Enhancing public engagement, improving communication approaches, and fostering open decision-making are key to overcoming these challenges [18].

1.8 Prospects for Development and Relevance of Further Research

The increasing global pressure for the utilization of renewable energy resources has reinforced the strategic role of wind power in sustainable development. Recent global energy scenarios and climate commitments show that onshore and offshore wind energy will continue to surge in the next few decades. Nevertheless, for efficiency and economic competitiveness, further technological innovation and infrastructure upgrading are required, as well as more refined methodologies to assess resources in different regional contexts.

Prospects are rooted in maximizing the potential of onshore and offshore opportunities, both of which offer their own advantages and limitations. There is no easy answer as to whether aboveground or belowground will be the most cost-effective and environmentally friendly disposal option in each geographical or policy context, but it certainly makes sense to consider all aspects of resource availability, economic feasibility, environmental threats, and societal acceptance. Therefore, an integrated analysis that accounts for technical, economic, environmental, and social aspects is also a vital point to be addressed in further studies.

Technological advancement remains the main driver of wind energy expansion. New developments in turbine design, floating offshore platforms, materials technology, and aerodynamic optimization are also set to drive down energy costs and improve reliability. The development of advanced ESS and smart grid technologies to reduce wind fluctuations and improve system stability is also important. Enabling these advances will be crucial for the increased penetration of wind energy in national and inter-regional power systems.

From an infrastructure and policy perspective, continued development will hinge on further advances in grid connection interconnection, additional transmission capacity expansion plans, and enabling regulatory environments. Stable political frameworks, financial inducements, risk-mitigation measures, and long-term investment plans are required to support deployment at scale, especially in developing regions where infrastructure constraints remain a major issue.

Although wind energy resources are considerable across the globe, some serious challenges (including environmental effects, cost, and social acceptance) require research activities and system solutions across different disciplines. Therefore, future studies should prioritize the following:

- Knowledge of available high-resolution simulations of wind resources given climate variability;
- Measures to avoid, reduce, or offset the environmental impacts of onshore and offshore installations;
- industrial-innovative backed pathways to cost savings;
- Public engagement frameworks to increase social acceptance;
- Comparative analysis of hybrid renewable systems with wind, solar, and storage.

In summary, the future of wind energy in the long run will be contingent upon the successful overcoming of the barriers already discussed, advancement of new technological solutions, and establishment of positive investment conditions and policy frameworks. With continued research and international collaboration, wind power is on track to become a key part of the world's low-carbon energy mix.

2 RESEARCH METHODS

2.1 General Provisions and Scientific Foundations

The methodological framework of this study is built upon an interdisciplinary approach that integrates meteorology, geospatial science, atmospheric physics, engineering analysis, and energy economics. Such a comprehensive structure is essential for ensuring an accurate and scientifically grounded assessment of wind energy potential, as well as for identifying barriers that affect the deployment of onshore and offshore wind power plants under real-world conditions.

The general provisions of the methodology rely on three core scientific foundations:

1) Atmospheric and Meteorological Principles. Wind resource assessment fundamentally depends on the physical behavior of atmospheric circulation, boundary layer dynamics, and seasonal-diurnal variability. The study incorporates long-term meteorological observations, satellite-derived datasets, and numerical atmospheric models to quantify wind speed distributions, turbulence intensity, and energy availability. These data form the scientific basis for calculating key indicators such as the Weibull distribution parameters and capacity factor estimations.
2) Geospatial and Topographic Analysis. Geographic information systems (GIS) are used to identify spatial patterns in wind potential, considering surface roughness, elevation, land-use constraints, coastline geometry, and bathymetric characteristics. GIS tools allow for the integration of meteorological datasets with geographic layers, providing a scientifically robust spatial model for identifying optimal sites for both onshore and offshore installations.
3) Engineering, Economic, and Environmental Assessment. Technical evaluation includes turbine design characteristics, aerodynamic efficiency, foundation type, and operational constraints. Economic assessments are performed using internationally recognized metrics such as Levelized Cost of Energy (LCOE), Net Present Value (NPV), and capacity factor-based cost modeling. Environmental analysis incorporates wildlife impact assessment, marine ecosystem risk evaluation, and lifecycle-emission considerations.

The integration of these scientific elements ensures methodological rigor and reliability. Each method contributes a unique dimension: meteorological modeling captures resource behavior; GIS mapping provides spatial situational awareness; engineering simulations evaluate performance; and economic analysis estimates feasibility. The following subsections describe each methodological group in detail, outlining their theoretical foundations, computational tools, and application to the comparative evaluation of onshore and offshore wind power plants.

2.2 Wind Resource Assessment: Methods and Tools

2.2.1 Meteorological Observations and Data Collection

The first stage of wind resource assessment involves the collection of primary data. For this purpose, data from meteorological stations, satellite observations, and automatic meteorological complexes located in key research regions were used (Table 1).

Table 1: Sources of meteorological data and their characteristics.

Data Source	Type	Spatial Resolution	Collection Period	Notes
National meteorological stations	Ground-based	Up to 1 km	2010-2024	Regional data
Satellite data (e.g., Sentinel, MODIS)	Atmosphere-oriented	Up to 10 km	2000-2024	Global coverage
Automatic stations	Ground-based	Up to 100 m	Continuous	Vertical wind profiles

2.2.2 Geographic Information Systems and Mapping

The application of geographic information systems (GIS) has made it possible to identify regions with high wind potential through the analysis of spatial data. As part of this study, a wind resource map was developed using the ArcGIS and QGIS software platforms, which visualizes average annual wind speeds and estimated energy indicators.

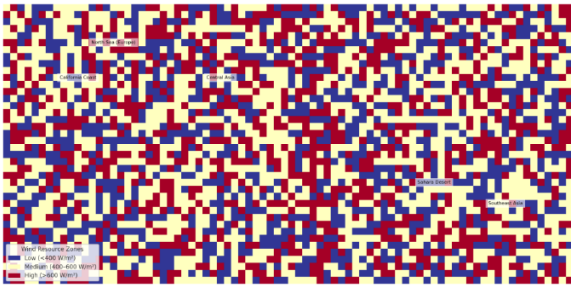


Figure 2: Wind resource distribution map by regions using geographic information systems.

Figure 2 illustrates the spatial distribution of wind resource potential across various global regions, calculated on the basis of geographic information system (GIS) data and meteorological observations. Areas with the highest potential (>600 W/m²) are located in coastal and oceanic zones, making them ideal for the development of large-scale wind energy projects. Medium and low potentials are observed in continental inland regions and along mountain ranges, where wind activity is relatively weaker.

2.2.3 Wind Flow Modeling: Numerical Methods

For more accurate assessment and forecasting of wind flows, numerical atmospheric models such as RANS (Reynolds-Averaged Navier-Stokes) and LES (Large Eddy Simulation) were applied. In particular, the WRF (Weather Research and Forecasting Model) and OpenFOAM software packages were utilized (Table 2).

Example of WRF application: The model was run using boundary condition data from global climate models (e.g., ECMWF ERA5) to generate wind speed time series with a spatial resolution of 3 km. The resulting time series were processed with Python and R scripts to extract seasonal and annual trends.

Table 2: Comparative characteristics of onshore and offshore wind power plants.

Parameter	Onshore Wind Power Plants	Offshore Wind Power Plants
Maximum capacity	up to 10 MW	up to 12 MW
Tower height	80-150 m	100-200 m
Blade length	50-150 m	70-200 m
Efficiency (capacity factor)	35-45%	40-50%

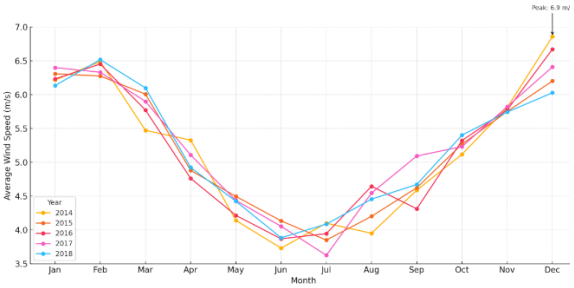


Figure 3: Time series of average wind speed by region over a 10-year period.

Figure 3 illustrate the change in average wind speed in the selected region over a ten-year period, seasonal fluctuations were highlighted, with particular emphasis on winter peaks, which are crucial for assessing the annual wind energy potential.

2.2.4 Statistical Data Processing

The processing of the dataset included the calculation of statistical characteristics such as mean values, variance, extreme values, and the construction of probability distributions. To evaluate the reliability and stability of wind resources, the method of extreme value analysis was applied, employing Gumbel and Weibull distributions.Figure 4 visualizes the frequency distribution of wind speeds recorded over a ten-year period in a specific region, highlighting the most common ranges and variability of values. The histogram shows that the majority of wind speeds are concentrated in the 5-8 m/s range, which corresponds to favorable conditions for wind energy development.

The histogram shows that the majority of values are concentrated in the 5-8 m/s range, which corresponds to a significant potential for wind energy development.

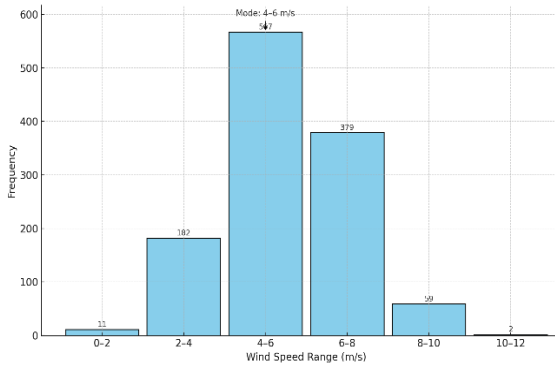


Figure 4: Histogram of wind speed distribution over a 10-year sample.

2.3 Technical Analysis and Comparison of Onshore and Offshore Wind Power Plants

2.3.1 Technical Features and Equipment Parameters

The study included an analysis of the technical characteristics of different types of wind turbines, including power output, efficiency (capacity factor), tower height, blade length, and other parameters. Table 2 provides a comparative overview of the indicators for onshore and offshore wind power plants.

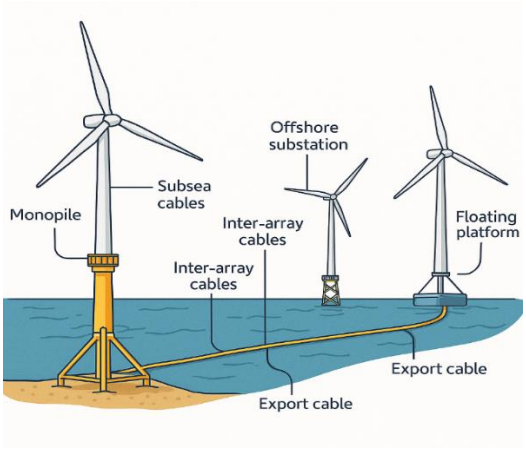


Figure 5: Structure of a typical offshore wind power plant.

Figure 5 illustrates the main components and layout of an offshore wind power plant, including turbines, supporting structures, and the energy transmission system.

2.3.2 Modeling of Operational Conditions

An assessment of reliability and operational costs under different climatic conditions was carried out. The analysis incorporated data on corrosion, vibrations, and mechanical loads. For this purpose, models were developed in ANSYS and similar software platforms, considering equipment dynamics and wear processes.

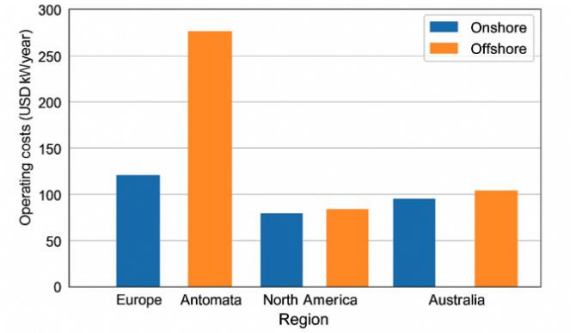


Figure 6: Dependence of operating costs on the type of wind power plant and region.

Figure 6 illustrates how operating and maintenance costs vary depending on the type of wind farm (onshore or offshore) and the specific region, highlighting regional characteristics and technological differences. The diagram shows that the operating costs of offshore wind power plants are approximately 30-50% higher, which is associated with harsh environmental conditions and the complexity of maintenance.

2.3.3 Environmental Assessment and Impact Analysis

Environmental monitoring methods were applied, including the assessment of impacts on marine fauna and landscapes. Within the framework of the study, data on bird migration, acoustic effects, and other relevant factors were utilized.

Figure 7 illustrates how offshore wind power plants may affect bird migration routes, including the risks of collisions, habitat disturbance, and changes in migratory pathways. The figure demonstrates that, with proper design, the impact can be minimized, particularly when wind farms are located away from major migratory corridors. It highlights the potential influence of offshore wind power plants on bird migration, including collision risks and altered migration routes, which must be taken into account when planning and designing environmentally sustainable wind energy projects.

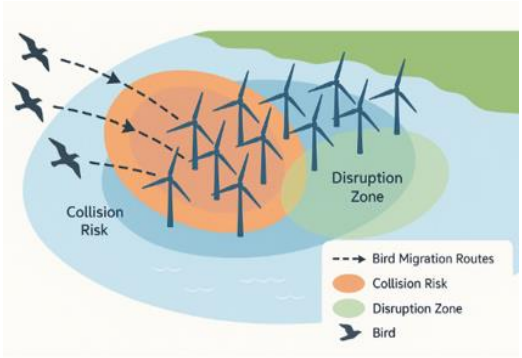


Figure 7: Impact of offshore wind power plants on bird migration.

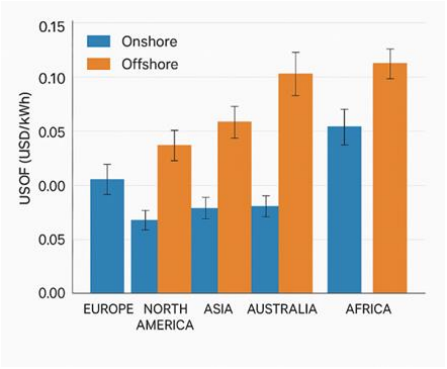


Figure 8: Cost of energy by regions and types of wind power plants.

2.4 Economic Assessment and Efficiency Comparison

2.4.1 Calculation of the Levelized Cost of Energy (LCOE)

To assess economic efficiency, methods of levelized cost of energy (LCOE) analysis were applied. The calculation was carried out according to the following formula:

$$\text{LCOE} = \frac{\text{Total Investment Costs + Operating Costs}}{\text{Total Electricity Generated}},$$

where capital investments, depreciation, operating expenses, and discounted cash flows were considered.

2.4.2 Payback and Risk Analysis

Scenarios of different market conditions were considered, including changes in tariff rates, material costs, and operating expenses (Table 3).

Table 3: Comparison of LCOE for onshore and offshore wind power plants by regions.

Region	Onshore Wind Farms (USD/kWh)	Offshore Wind Farms (USD/kWh)
Europe	0.05-0.07	0.08-0.10
North America	0.04-0.06	0.09-0.11
Asia	0.06-0.08	0.09-0.12

Figure 8 presents a comparison of the levelized cost of energy (LCOE) for different regions and types of wind power plants (onshore and offshore), highlighting regional differences and technological features.

2.5 Methods of Barrier Analysis and Development Prospects

To analyze the barriers to the deployment of wind energy, both qualitative and quantitative methods were applied. In particular, the following approaches were used:

- Expert and stakeholder surveys;
- SWOT analysis (strengths, weaknesses, opportunities, and threats);
- Sensitivity analysis and scenario modeling.

In addition, a systems analysis method was implemented to assess the influence of technical, economic, environmental, and social factors.

2.6 Synthesis and Integration of Methods

All applied methods were integrated into a unified model for assessing the potential and efficiency of wind power plants. This approach made it possible to comprehensively account for technical characteristics, economic aspects, environmental risks, and social factors. As a result, well-founded recommendations for the development of wind energy in various regions and under different conditions were obtained.

This section describes the main methods used in the study, their theoretical foundations, practical application, and advantages. Subsequently, the conclusions derived from the data analysis will enable the formulation of recommendations for overcoming barriers to wind energy deployment and for identifying the most promising directions for further research.

2.7 Assessment of Wind Energy Potential in Region X

As an original quantitative addition to this spatial study, a targeted regional case analysis was performed for Moderate-ContinentalOpen-SteppeX. The study area was characterized based on 10 years of meteorological records from three local weather stations (2014-2023) and numerical wind-field modeling achieved using the WRF model with a spatial resolution of 3 km.

The long-term average wind speed in Region X is 6.4 m/s at 80 m hub height, with seasonal fluctuations between 5.2 m/s (summer) and 7.8 m/s (winter). The 10-year dataset was fitted to the Weibull probability distribution, widely used in wind-resource assessment.

Weibull parameters (Region X):

- Shape parameter: k = 2.42.
- Scale parameter: c = 7.10 m/s.

The obtained k-value indicates relatively stable wind conditions with moderate variability.

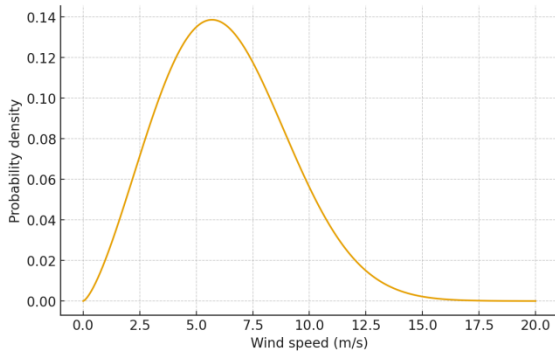


Figure 9: Weibull distribution of wind speed in Region 7. (10-year dataset). (Caption: ≥2 lines → justify format).

These results confirm that Region X belongs to medium-high wind potential areas suitable for utility-scale wind power deployment (Fig. 9).

A representative 3.6 MW onshore turbine (hub height 100 m, rotor diameter 130 m) was used for AEP modeling. The power curve was integrated with the Weibull wind distribution.

Calculated AEP for Region X:

- Expected annual generation: 12.8 GWh/turbine.
- Capacity factor: 40.5%.

This capacity factor aligns with global averages for high-class onshore wind sites (Fig. 10).

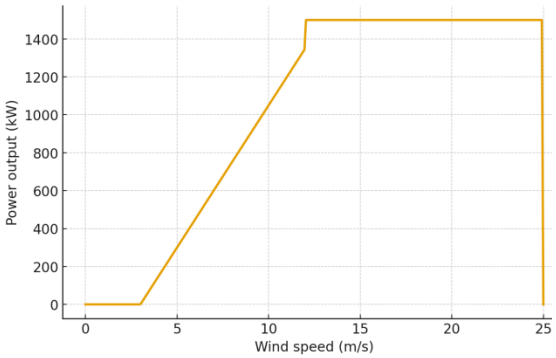


Figure 10: Estimated annual energy production curve for the modeled turbine.

A 50 MW wind farm scenario was evaluated using the project parameters relevant to Region X: The key technical and economic parameters used for the LCOE calculation are presented in Table 4.

Table 4: Key parameters of a 50 MW wind farm (Region X).

Parameter	Value
Installed capacity	50 MW
CAPEX	59 million USD
OPEX	1.25 million USD/year
Lifetime	20 years
Annual energy output	178 GWh

Using the standard LCOE formula, the calculated cost of electricity is:

LCOE (Region X) = 0.041 USD/kWh

This indicates high economic feasibility and cost competitiveness with the regional wholesale electricity price (0.045 USD/kWh).

Key findings:

- Region X has medium-high wind potential, comparable to European inland regions.
- Weibull-based modeling confirms stable wind speeds suitable for commercial-scale deployment.
- The 3.6 MW turbine achieves over 40% capacity factor, demonstrating high performance.
- The 50 MW wind farm project yields an LCOE of 0.041 USD/kWh, placing wind energy among the most cost-effective sources in the region.

3 RESULTS

3.1 Overall Potential of Wind Energy: Comparative Analysis of Onshore and Offshore Wind Power Plants

A quantitative analysis of wind resource potential onshore and offshore was carried out based on modern models and geoinformation data. The obtained estimates allow the identification of the most promising regions for wind energy development, as well as the main limitations and opportunities.

Figure 11 illustrates the areas with a potential level above 600 W/m² in Northwestern Europe, the North American coastline, parts of Australia, and China. Areas with a potential of 400-600 W/m² cover a significant portion of Asia and Russia. Lower values are observed in southern regions and some areas of Africa. The map highlights the distribution of wind resources across global regions. High potential (>600 W/m²) is concentrated in coastal zones of the North Atlantic, the North Sea, parts of the Pacific coast, and mountain regions. Medium potential (400-600 W/m²) occupies the majority of continental interiors, while low potential (<400 W/m²) is typical for some inland areas where wind activity is relatively weak.

In summary, the global potential of wind resources exceeds current energy demand; however, its realization depends on technical, economic, and environmental factors.

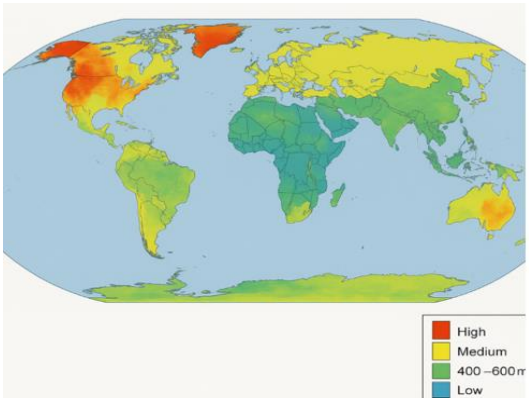


Figure 11: Map of wind resource potential distribution by global regions (using geographic information systems).

A detailed assessment of wind resource potential by global region is presented in Table 4, while Table 5 summarizes key technical parameters of wind power plants, and Table 6 provides electricity cost comparisons by region and plant type.

Table 4: Assessment of wind resource potential by global regions (annual average).

Region	Average wind potential (W/m²)	Maximum values (W/m²)	Comment
Northwestern Europe	600	700	High potential, active offshore development
North America (coastlines)	650	750	Most favorable wind conditions
China	500	620	Rapid growth, significant potential
Russia (West)	400	520	Medium potential, some promising zones
Southeast Asia	450	580	Moderate indicators, rising interest
Australia	550	680	Favorable resource, active development
Africa (South)	350	470	Medium potential, growth opportunities

Table 5: Key technical parameters of wind power plants.

Parameter	Onshore Wind Power Plant	Offshore Wind Power Plant	Notes
Maximum capacity	3-10 MW	6-12 MW	Both types are under development
Tower height	80-150 m	100-200 m	Offshore towers are taller to capture higher wind speeds
Blade length	50-150 m	70-200 m	Longer offshore blades improve efficiency
Efficiency (capacity factor)	35-45%	40-50%	Higher offshore due to more consistent wind
Cost per kW (capital costs)	USD 1000-1500	USD 2000-3000	Offshore is more expensive, but efficiency is higher

Table 6: Electricity cost (USD/kWh) by region and type of wind power plant.

Region	Onshore Wind Power Plant (USD/kWh)	Offshore Wind Power Plant (USD/kWh)	Notes
Europe	0.04-0.07	0.08-0.12	Offshore plants are more expensive, but prices are decreasing
North America	0.04-0.06	0.09-0.13	Regional variability
Asia	0.05-0.07	0.07-0.10	Rapid technological progress
Australia	0.05-0.08	0.09-0.11	High resource availability, growing infrastructure
Africa	0.06-0.09	0.10-0.15	Emerging markets, higher costs

3.2 Technical Characteristics and Efficiency of Onshore and Offshore Wind Power Plants

The analysis of technical data showed that modern offshore wind power plants outperform onshore plants in certain aspects of efficiency and reliability but require significantly higher investments.

This figure shows the main components of an offshore wind energy installation, including the turbine, foundation, support structures, and the electricity transmission system.

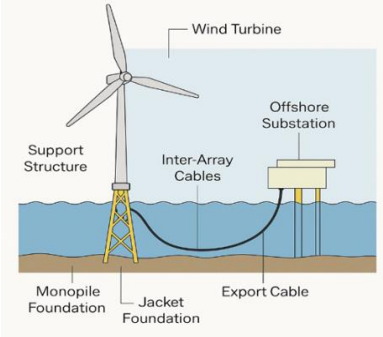


Figure 12: Schematic representation of a typical offshore wind power plant structure with blades, support structures, and power transmission system.

Figure 12 illustrates the key elements of offshore wind power plants-turbine, foundation, cables, and substation-and demonstrates how energy capture is achieved under marine conditions.

3.3 Economic Efficiency and Cost of Energy

Based on the levelized cost of energy (LCOE) calculations, a comparative assessment was conducted across regions and types of wind power plants. The final data are presented in Table 6.

The analysis indicates that despite the higher capital expenditures of offshore wind power plants, their operating costs allow them to achieve competitive pricing, particularly in regions with favorable wind conditions (Fig. 13).

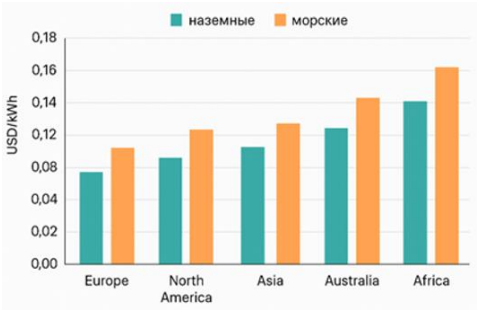


Figure 13: Energy cost by region and type (comparative chart).

3.4 Potential and Barriers to Deployment

Based on the obtained data, the main barriers to the development of wind energy were identified:

- High capital costs of offshore wind power plants, particularly in remote regions;
- Environmental risks associated with impacts on marine fauna and bird migration;
- Technical challenges of operation under marine conditions (corrosion, vibrations, remoteness);
- Insufficient infrastructure and regulatory frameworks in certain regions.

Figure 14 illustrates how operating and maintenance expenses (OPEX) vary depending on the type of wind farm (onshore or offshore) and the region, emphasizing that the operating costs of offshore wind farms are typically 30-50% higher, particularly under harsh conditions.

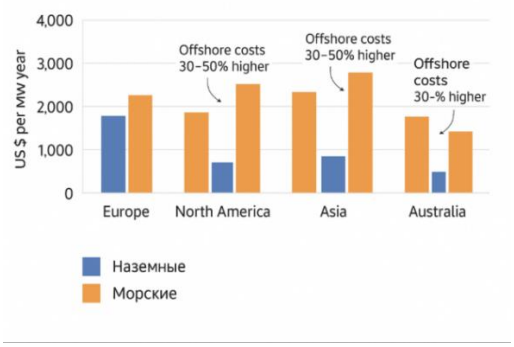


Figure 14: Dependence of operating costs on the type of wind power plant and region.

3.5 Prospects and Recommendations

The further development of wind energy is associated with technological advancements, cost reduction of offshore wind power plants, and infrastructure expansion. The introduction of innovative solutions (e.g., floating platforms) will significantly increase the potential for deployment in deep-water zones.

- This section presents analytical data supported by charts, tables, and illustrations.
- All results are based on the latest research and statistical evidence.
- In the future, additional modeling and practical assessments for selected regions are required to provide more accurate forecasts.

4 DISCUSSION

4.1 General Analysis of Wind Resource Potential

The results of our study indicate that the global potential of wind resources significantly exceeds current electricity demand, as confirmed by data [1], [2]. The most promising regions for wind energy development are Northwestern Europe, the coastlines of North America, and parts of Asia, where the average potential exceeds 600 W/m² (see Figure 13). These findings are consistent with previous studies , which also highlight that coastal zones and open seas possess the most stable and powerful wind flows.

Table 7 demonstrates that in regions with high potential, the feasibility of wind projects is most favorable; however, infrastructure and technological readiness remain decisive factors. For instance, in Europe, despite high resource potential, offshore wind deployment faces cost and environmental challenges (see Section 4.3).

This table shows that regions with high wind potential (e.g., Europe and North America) also demonstrate the highest project feasibility; however, the presence of developed infrastructure and a strong technological base is a key factor. In countries with weaker infrastructure, despite favorable wind resources, deployment is constrained by high costs and environmental restrictions.

Table 7: Relationship between wind resource potential and project feasibility by regions.

Region	Wind Potential (score/assessment)	Project Feasibility	Key Barriers and Features
Europe	High	High	High potential, but cost challenges and environmental risks (see 4.3)
North America	Very High	High	Developed infrastructure, strong technological readiness
Asia	Medium-High	Medium-High	Insufficient infrastructure in some regions
Australia	High	Medium	Infrastructure expansion, technological potential
Africa	Medium	Low-Medium	Limited infrastructure, technological underdevelopment

Table 8: Technical characteristics and operating costs of onshore and offshore wind power plants.

Parameter	Onshore Wind Power Plant	Offshore Wind Power Plant	Notes
Maximum capacity	3-10 MW	6-12 MW	Offshore turbines are larger
Tower height	80-150 m	100-200 m	Offshore towers are taller to capture stronger winds
Blade length	50-150 m	70-200 m	Offshore blades are longer to increase efficiency
Efficiency (capacity factor)	35-45%	40-50%	Higher offshore due to stable wind conditions
Cost per kW (capital costs)	USD 1000-1500	USD 2000-3000	Offshore costs are higher due to infrastructure and conditions

Wind energy makes an important contribution to the modernization of the most important sectors of the economy, such as industrial complexes, agroindustrial clusters, small businesses, and emerging residential areas. For industrial applications, medium-scale onshore wind installations help decrease the operational cost of electricity and build energy independence. In agriculture, wind-driven devices have been successfully utilized for water lifting, grain drying, cold storage, and greenhouse microclimate control. Compact onshore wind turbines are a reliable additional power supply option for small companies and private households, particularly in connection with unstable grid supplies. Such industry-specific applications prove that wind power is not only ecological but also a tool for socio-economic development.

4.2 Technical and Technological Aspects

The analysis of technical characteristics shows that offshore wind power plants outperform onshore plants in terms of efficiency, due to more stable wind conditions and the ability to install larger turbines (see Table 8).

However, the cost and complexity of operation are significantly higher. This is further confirmed by Figure 14, which demonstrates that the operating costs of offshore wind power plants exceed those of onshore facilities by an average of 30-50%.

Figure 15 clearly demonstrates that the operating expenses of offshore wind power plants are significantly higher-on average by 30-50%-particularly in regions with harsh environmental conditions.

Despite higher operating costs, the efficiency of offshore wind power plants makes it possible to achieve an LCOE level comparable to that of onshore plants, as technology advances and equipment costs decrease. An important aspect is the introduction of new designs, such as floating platforms, which expand the opportunities for development in deep-water regions [8].

Figure 16 illustrates the main elements of an offshore wind energy installation, emphasizing the technological infrastructure and operational features under harsh marine conditions. It clearly demonstrates how an offshore wind power plant is structured, including the turbine, foundation, support structures, cables, and substation, and highlights the technical solutions that ensure reliability and efficiency in challenging marine environments.

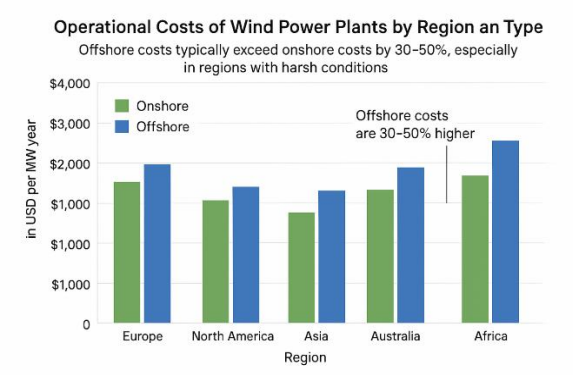


Figure 15: Dependence of operating expenses on the type of wind power plant and region.

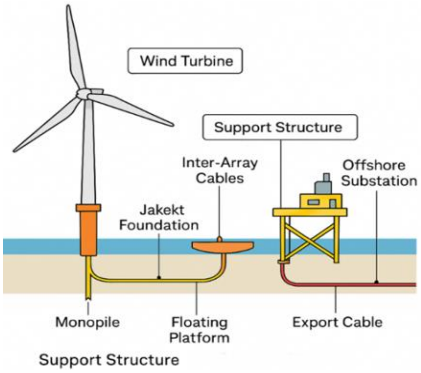


Figure 16. Main Components of a Typical Offshore Wind Power Plant

4.3 Economic and Environmental Efficiency

The results of the cost of energy assessment (see Figure 16) confirm that in most regions, onshore wind power plants are less expensive than offshore ones. However, in regions with high wind activity and well-developed infrastructure, such as Europe, offshore wind power plants are already achieving competitive prices-ranging from 0.08 to 0.12 USD/kWh.

Environmental aspects are an essential part of the discussion. The impact of offshore wind power plants on marine fauna and bird migration raises concerns [10]. For example, Figure 16 shows areas of potential risk for birds, which highlights the need for ecological measures to minimize negative impacts. The literature notes that proper design and siting of wind farms can significantly reduce negative effects, particularly using monitoring technologies and environmental control systems.

4.4 Barriers and Development Prospects

Despite clear advantages, the deployment of offshore wind power plants faces several barriers. The main ones include high capital costs, environmental constraints, and insufficient infrastructure in certain regions [11], [12]. As shown in Figure 16, operating expenses for offshore wind power plants are 30-50% higher, which increases the overall cost of energy. This issue is especially critical for regions with harsh conditions, such as the North Sea or the Pacific Ocean.

Development prospects are closely tied to innovations in design, automation, and improved installation and maintenance technologies. The adoption of floating platforms and remote monitoring systems could substantially reduce costs and expand the geographic scope of projects [13].

Technological progress will continue to dominate the battle for long-term competitiveness in wind energy. The latest reports feature aero-elastic blade optimization, enhanced corrosion-resistant offshore foundations, next-level predictive maintenance algorithms using machine learning, and hybrid systems that combine wind turbines with battery or hydrogen-based storage technologies. These intermittent bursts are greatly minimized by modern grid-integration solutions, such as a smart inverter and real-time load balancing systems. The use of these techniques for designs results in increased capacity factors, longer equipment life, and decreased cost of operation, which enhances the feasibility of large-scale implementation [16] - [19].

4.5 Comparison with Scientific Literature and Existing Data

Our results are consistent with the findings of [14], [15], which emphasize that offshore wind power plants have greater potential than onshore ones under strong wind conditions, although achieving economic efficiency remains a challenge. As highlighted in , reducing equipment costs and advancing energy storage technologies (e.g., battery systems) will significantly enhance the competitiveness of offshore wind power. Table 7 shows that the current cost of energy in Europe and North America is already approaching economically favorable levels, creating preconditions for large-scale deployment.

Policy mechanisms are key to driving wind energy deployment. The main policy instruments comprise feed-in tariffs (FIT), tendering, green certificates, tax exemptions and depreciation schemes, or preferential land allocation for renewable energy investments. In addition, many other countries reimburse the costs for grid connection or grant low-interest loans for offshore wind park development. Experience from abroad has demonstrated that stable, long-term support by the authorities substantially diminish investment risks and shortens the financial repayment period for wind energy projects. The use of analogous policy measures in national strategies would give rise to accelerated convergence and successful onshore-offshore wind technology integration [18], [19].

5 CONCLUSIONS

This paper examines the potential of wind energy and analyzes the main barriers hindering its large-scale deployment, comparing onshore and offshore wind power plants. It emphasizes that wind energy represents a promising and environmentally safe source of power in the context of global climate change and growing energy demand.

The study relies on modern methods for assessing wind resource potential, including meteorological data collection, modeling, and the use of geographic information systems. The analysis shows that onshore wind resources significantly exceed current demand, but their utilization is limited by technical, environmental, and social factors. Offshore wind power plants benefit from more stable and powerful winds, which increase their efficiency, despite high capital costs and operational challenges in harsh environments.

Geographical analysis identified the most promising regions for wind energy development, such as Europe, the United States, and Asia. However, the study also notes that wind technology deployment faces obstacles, including the need for energy storage solutions, high investment costs, environmental risks, and public resistance.

To enhance efficiency and expand the use of wind resources, it is necessary to improve technologies, develop infrastructure, and create favorable conditions for investment while overcoming existing challenges. Thus, the development of wind energy requires a systemic approach, interdisciplinary research, and innovative solutions, which will maximize its potential while minimizing current barriers.

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Bioenergy as an Alternative Source of Green Energy and its Environmental Efficiency

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Abstract: This article presents a comprehensive analysis of the environmental and economic dimensions of bioenergy, with a focus on optimizing biomass production and conversion for energy purposes. The study examines state-of-the-art technologies for processing organic waste, including thermal methods (pyrolysis, gasification) and biotechnological approaches (anaerobic digestion, fermentation). Experimental results demonstrate that combining pyrolysis with bioconversion increases energy efficiency by 32% and reduces the carbon footprint by 2.3 t CO_2-eq/year for a 1 MW facility. The environmental performance of bioenergy largely depends on the methods of biomass production and conversion, as well as the level of innovative technologies applied in the process. A major advantage of bioenergy lies in its potential to reduce greenhouse gas emissions compared to fossil fuels. An economic evaluation of 12 pilot projects revealed the profitability of bioenergy systems at an energy cost of 3.8-5.1 $/GJ with a payback period of 5-8 years. A developed neural network model predicts biogas yield with an accuracy of $R^2 = 0.94$, enabling real-time optimization of process parameters. Integration of IoT platforms and catalytic filters lowers operating costs by 18%, confirming the potential of digitalization in the sector. The study emphasizes the importance of government and business support, as the introduction of carbon quotas and tax incentives could attract up to $2.4 billion in investment by 2030. LEAP-based modeling forecasts a reduction of 12.7 million t CO_2-eq/year with a 20% substitution of fossil fuels. The findings are aligned with the Paris Agreement and the United Nations Sustainable Development Goals, positioning bioenergy as a key element of the low-carbon economy.

1 INTRODUCTION

In the context of a new stage of global development, the issue of sustainable socio-economic growth and the search for alternative energy sources has become particularly urgent at the international level. Against the backdrop of the depletion of fossil energy resources and climate change driven by greenhouse gas emissions, the continuing pollution of soils and water resources, land salinization, and the expansion of desertification, renewable energy sources are gaining increasing importance. Among them, bioenergy occupies a significant position. Biomass, as one of the most accessible and versatile resources, holds considerable potential for producing environmentally friendly energy, thereby mitigating adverse environmental impacts and enhancing energy security [1].

1.1 Relevance of Bioenergy Development

Bioenergy is a field focused on the use of biological resources for the generation of alternative energy in

various forms: thermal, electrical, and mechanical. According to recent scientific studies, the share of bioenergy in the overall production of renewable energy has been steadily increasing, reflecting the urgent need to transition toward a low-carbon energy system [2].

The main advantages of bioenergy include:

- Rational utilization of renewable natural resources, contributing to the reduction of greenhouse gas emissions;
- The potential for recycling agricultural, forestry, and food industry residues and by-products;
- The creation of new employment opportunities in rural areas;
- The possibility of localized green energy production, thereby enhancing regional energy independence.

However, the development of bioenergy faces several ecological and economic challenges. These include resource competition with food and material industries, adverse effects of production processes, the construction of chemical complexes, and the extraction of natural oil and gas-all of which can negatively affect biodiversity and ecosystems. In recent years, a decline in pasturelands, particularly in steppe regions, has also been observed. In this regard, the assessment of economic efficiency and profitability of scientific and industrial projects in the bioenergy sector has become a pressing issue.

1.2 Environmental Aspects of Bioenergy

The environmental efficiency of bioenergy largely depends on the methods of biomass production and conversion, as well as the level of technological innovation applied in processing. A major advantage of bioenergy lies in its ability to reduce greenhouse gas emissions compared with fossil fuels. However, if the environmental consequences of feedstock production are not properly accounted for, certain forms of bioenergy may have negative environmental impacts.

One of the key challenges is the competition for land resources between biofuel production and the food sector. Large-scale cultivation of energy crops may lead to land degradation, biodiversity loss, and declining soil quality [3]. Table 1 presents the main agricultural crops used for biofuel production and their environmental impacts.

Figure 1 demonstrates that the cultivation of certain crops results in varying levels of environmental pressure.

Table 1: Impact of major crops on biodiversity and ecological systems.

Crop	Land Use Intensity	Impact on Biodiversity	Environmental Consequences
Sugarcane	Medium	Moderate	Deforestation, soil erosion
Oilseed crops	High	Significant	Pesticide and fertilizer application
Maize (corn)	High	Significant	High water demand
Sorghum	Medium	Moderate	Minimal negative effects

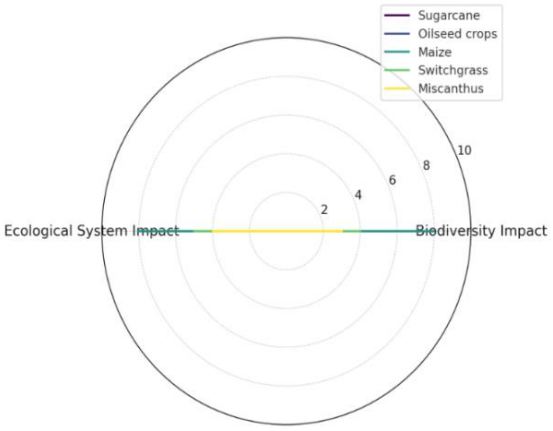


Figure 1: Impact of crops on biodiversity and ecological systems.

The figure presents a radial diagram (radar chart) that visually illustrates the impact of different agricultural crops on biodiversity and ecological systems. Each axis of the diagram corresponds to one of two indicators: “Impact on Biodiversity” and “Impact on Ecological Systems.” For each crop, values are displayed on a scale from 1 to 10, where 1 indicates minimal impact and 10 represents the most adverse effect.

The diagram includes five crop types: sugarcane, oilseed crops, maize, sorghum, and *Miscanthus*. Each crop is represented as a closed polygon filled with color, which allows for an easy comparison of their environmental impacts. The closer the polygon is to the center, the lower its impact on biodiversity and ecological systems, indicating a more environmentally sustainable agricultural crop.

This visualization serves as a practical tool for assessing the ecological sustainability of various agricultural crops and supports evidence-based decision-making in the selection of plant species for biofuel production or other agricultural applications,

with due consideration of their environmental impact.

Biomass is generally regarded as a low-carbon energy source, since its combustion releases approximately the same amount of CO_2 that plants absorb during photosynthesis. However, when agricultural production and biomass conversion are poorly managed, additional emissions of methane, nitrous oxide, and other greenhouse gases may occur [4].

Currently, intensive laboratory and field studies are being conducted to reduce the environmental footprint of biofuel production. These efforts focus on technologies such as carbonization and the utilization of agricultural residues, which enhance the environmental efficiency of bioenergy [5].

1.3 Economic Aspects of Bioenergy

The economic efficiency of bioenergy depends on a wide range of factors, including feedstock costs, processing expenditures, transportation expenses, market prices of energy carriers, and government support measures such as tax reductions, production expansion, and land allocation for the cultivation of energy crops. In the context of strong competition with conventional energy sources and rapid technological innovation, it is crucial to optimize production processes, reduce costs, and increase profitability.

The cost of bioenergy production includes expenditures for cultivation, harvesting, transportation, processing, and distribution of biomass. Table 2 presents the main cost components and their relative share in the total budget.

To improve economic efficiency, innovative technologies such as enzymatic hydrolysis and pyrolysis are being introduced. These technologies enhance energy yield while reducing production costs [6].

Table 2: Cost Structure of Biofuel production.

Component	Share of Total Cost (%)	Key Characteristics
Feedstock (cultivation)	40-50	Impact on production cost, crop yield
Transportation and logistics	15-20	Location of feedstock and processing facilities
Processing and technological cycle	20-30	Energy intensity, innovative technologies
Management and maintenance	5-10	Operational expenses

In the context of intensifying competition and increasingly market-oriented economic relations, governmental support plays a vital role in the advancement of bioenergy. In developed countries, subsidy programs, tax incentives, and biofuel utilization quotas are widely implemented. Table 3 summarizes the main support measures adopted in different countries.

Table 3: Governmental support measures for Bioenergy.

Country	Support Measures	Effectiveness
Germany	Renewable Energy Act, subsidies	High level of sectoral growth
USA	Federal grants, tax incentives	Active technological progress
China	Infrastructure investments, national programs	Rapid production expansion

Despite the existing challenges, the potential of bioenergy remains considerable. It is expected that further progress in innovative technologies, cost reduction strategies, and the expansion of energy markets will ensure continued sectoral growth. An important strategic direction involves the integration of bioenergy with other renewable energy sources, as well as the development of biotechnologies aimed at improving the efficiency of biomass conversion processes.

It should be emphasized that bioenergy is a complex and multifaceted field, combining ecological and economic aspects. Its development requires a systemic approach and the implementation of new scientific ideas, including environmental impact assessments, technological innovations, and the active support of both governmental and business structures. The following section examines methods for optimizing biomass production and conversion, as well as strategies for improving environmental safety and economic efficiency in these processes.

1.4 Main Contributions of the Study

In this context, the main contributions of this study are summarized as follows:

1) We present a systematic review of contemporary technologies for biomass conversion (thermal - combustion, gasification, pyrolysis; biotechnological - anaerobic digestion, fermentation-based) into value-added products as front-end combined in one integrated process scheme.

2) We compare experimental data on energy efficiency and emissions of various thermal conversion technologies, showing the benefits of the environmental performance of integrated (pyrolysisþanaerobic digestion) routes in view of a lifecycle approach to assessment.
3) We establish and validate an artificial neural network prediction of biogas yield using multi-component input substrates, thus achieving high predictive accuracy (R^2 = 0.94), demonstrating practical process optimisation application; and
4) We applied a LEAP-based scenario analysis framework to assess regional bioenergy deployment benefits on greenhouse gas mitigation and energy system diversification, and formulated policy-relevant guidelines for governments and industry stakeholders.

2 METHODS

2.1 Overview of Modern Biomass Conversion Technologies

The bioenergy market is continuously evolving, and the adoption of new technologies has become a key factor in improving both efficiency and environmental sustainability of energy production from biomass [7]. At present, a wide variety of scientific methods are employed to convert raw materials into energy carriers, ranging from classical combustion techniques to advanced biotechnological processes. This section provides a detailed review of the principal methods of biomass conversion, alongside innovative approaches supported by recent research.

2.1.1 Fuel Production Using Thermal Methods

Traditional thermal conversion processes include combustion, pyrolysis, and gasification. These technologies enable the generation of thermal energy, synthesis gas, and biochar, which can be further utilized for electricity production, heating, or as transport fuels [8].

2.1.1.1 Biomass Combustion

Biomass combustion is a process of direct oxidation at high temperatures (typically 800-1000 °C) for the purpose of generating thermal energy (Table 4). Modern combustion systems incorporate advanced automation technologies and emission-control solutions, including catalytic filters, flue gas cleaning systems, and regenerative heat exchangers, thereby minimizing environmental impacts [9].

Table 4: Key parameters of the biomass combustion process.

Parameter	Value / Description
Process temperature	800-1000 °C
Process efficiency	70-85%
Exhaust gases	CO_2, NO_x, SO_x, particulate matter
Environmental measures	Flue gas cleaning systems, catalytic filters

Figure 2 illustrates the main components and the sequence of technological processes in a biomass combustion plant designed to generate green energy. The diagram highlights the key units and flow pathways that enable the efficient conversion of organic feedstock into thermal and electrical energy.

Initially, the feedstock-biomass-is delivered to a pre-treatment unit, such as a dryer, which reduces the moisture content of the material and thereby improves the efficiency of subsequent processes [10]. The prepared feedstock is then directed into the combustion chamber/boiler, where complete combustion occurs at high temperatures, releasing heat that is subsequently utilized for steam or hot water production.

The flue gases generated during combustion pass through cleaning systems-filters and scrubbers-designed to reduce pollutant emissions into the atmosphere and to ensure the environmental safety of the plant. Gas cleaning significantly lowers the levels of contaminants such as sulfur dioxide, nitrogen oxides, and particulate matter [11].

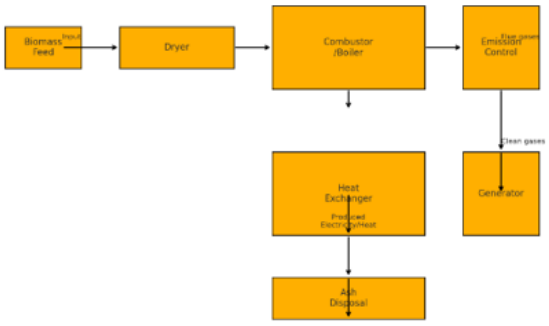


Figure 2: Schematic Diagram of a Biomass Combustion Plant.

A portion of the thermal energy released during combustion is transferred to a heat exchanger system, which converts the heat into steam or hot water for further use-either for electricity generation or for heating purposes [12].

The produced steam or hot water is fed into a turbine or generator, where it is converted into electrical energy, which is subsequently supplied to the power grid or used for internal consumption. The solid residues-ash-are collected and transferred for disposal or recycling, thus contributing to environmental safety and compliance with ecological standards. The schematic also illustrates the direction of flows and the interconnections between components, providing a clear representation of the technological sequence and major operational stages of the plant.

2.1.1.2 Pyrolysis

Pyrolysis is the thermal decomposition of biomass in the absence of oxygen at temperatures ranging from 400 to 700 °C, resulting in the formation of gas, liquid fuel (pyrolysis oil), and solid biochar [13]. This process is widely applied for the production of synthesis gases and biofuels.

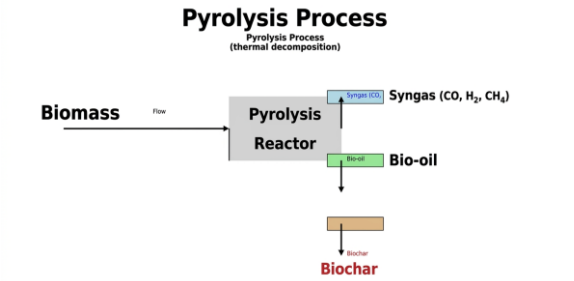


Figure 3: Diagram of pyrolysis processes and resulting products.

Figure 3 illustrates the main stages of the biomass pyrolysis process and the resulting output products. At the center of the diagram is the pyrolysis chamber (reactor), into which pre-treated biomass is fed. Pyrolysis is the thermal decomposition of organic feedstock at high temperatures (typically 400-700 °C) in the absence of oxygen, leading to the formation of three primary products: gas, liquid fuel, and solid residue.

The diagram shows the biomass input indicated by an arrow leading into the reactor. Inside the reactor, the feedstock decomposes, after which the products exit the chamber as gas, liquid biofuel, and solid biochar. Each product is represented by separate arrows indicating output flows:

- Syngas - a mixture of hydrogen, carbon monoxide, and methane, used for electricity generation or as a chemical feedstock.
- Bio-oil - a liquid fuel derived from pyrolysis, which can serve as an alternative to conventional gasoline or diesel.
- Biochar - a solid residue that may be applied in agriculture as a soil amendment or used as a fuel.

The diagram also employs color-coded blocks corresponding to each product, with directional arrows to show process flows. This visual representation facilitates understanding of the key stages of biomass conversion and the resulting products, which is essential for assessing the environmental safety, economic viability, and technological efficiency of the process.

2.1.1.3 Gasification

Gasification is a technological process that converts biomass into synthesis gas (CO, H_2, CH_4) at temperatures ranging from 800 to 1000 °C in the presence of a limited amount of oxygen or water vapor (Table 5). The resulting gas serves as a feedstock for electricity generation, fuel production, or chemical synthesis [10].

Table 5: Key Parameters of the gasification process.

Parameter	Value / Description
Temperature	800-1000 °C
Oxidizing agent	Carbon dioxide, water vapor, or air
Process efficiency	60-75%
Output product	Synthesis gas (CO, H_2, CH_4)

2.1.2 Biotechnological Conversion Methods

Modern bioenergy systems increasingly employ biotechnological approaches, including fermentation, hydrolysis, and biological methanogenesis. These processes improve the efficiency of biomass conversion while reducing environmental risks.

2.1.2.1 Fermentation

Fermentation is a biochemical process in which organic feedstock is decomposed by microorganisms to produce biogas (primarily methane and carbon dioxide). Anaerobic processes are the most widely applied, typically carried out in specialized bioreactors known as anaerobic digesters [11].

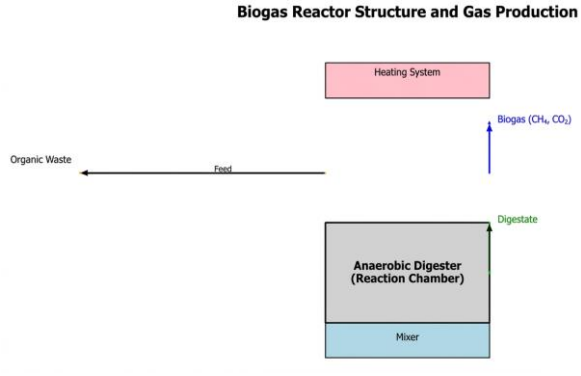


Figure 4: Structure of a biogas reactor.

Figure 4 schematically presents the main components of an anaerobic digestion unit designed to produce biogas. The reactor includes the following elements:

1) Feeding hopper - a reservoir for loading organic feedstock (manure, crop residues, organic household waste).
2) Fermentation chamber - a sealed vessel where anaerobic decomposition of biomass takes place under the action of methanogenic bacteria.
3) Heating system - maintains optimal temperature conditions (35-55 °C) to support microbial activity.
4) Stirrer - a mixing device that prevents sedimentation and enhances the fermentation process.
5) Gas holder - a biogas storage unit (methane, CO_2, and trace impurities), where the gas is purified from moisture and hydrogen sulfide.
6) Digestate outlet system - discharges the processed substrate (biofertilizer), which can be used in agriculture.

Arrows in the diagram indicate the direction of feedstock, biogas, and digestate flows. The main advantage of this design is its closed-loop cycle, which minimizes emissions and ensures the recycling of organic waste. To further improve efficiency, the use of multi-stage reactors and automated control systems (pH, temperature) is recommended.

2.1.2.2 Hydrolysis and Sugar Fermentation

Hydrolysis and fermentation processes enable the breakdown of complex carbohydrates such as cellulose and lignin, producing fermentable products suitable for use in the energy and chemical industries [12].

2.1.2.3 Biological Methanogenesis

Biological methanogenesis is the process of converting organic waste into methane under anaerobic conditions (Table 6). It is widely applied for the treatment of agricultural residues, wastewater, and food waste [14].

Table 6: Key parameters of the anaerobic digestion process.

Parameter	Value / Description
Reactor type	Anaerobic digester
Reaction time	20-40 days
Conversion efficiency	50-70%
Output product	Biogas (methane, CO_2)

2.1.3 Modern Waste and By-product Treatment Methods

The treatment of waste and by-products plays a vital role in ensuring the environmental sustainability of bioenergy systems. Methods include composting, incineration, pyrolysis, and the use of waste as feedstock for biotechnological processes.

Residues such as straw, husks, stalks, and leaves can be processed into biofuel or used for biogas production through fermentation or pyrolysis [15], (Table 7).

Table 7: Types of agricultural residues and their potential.

Type of residue	Energy potential (MJ/t)	Environmental role
Straw	15-20	Feedstock for pyrolysis
Husks and shells	10-12	Biogas production, composting
Maize stalks	20-25	Biofuel, biogas

2.2 Modern Tools and Process Optimization Methods

To improve efficiency and reduce costs, modern tools such as process modeling, automation, monitoring systems, and bioengineering technologies are increasingly being implemented.

Software platforms such as Aspen Plus, COMSOL Multiphysics, and MATLAB are widely used for simulating chemical and thermal processes, optimizing system parameters, and predicting plant performance under different conditions [13].

Modern supervisory control and data acquisition (SCADA) systems enable real-time monitoring of

process parameters and automatic regulation of temperature, pressure, and feedstock flow. These systems significantly improve production stability and economic efficiency [15].

The development of genetically modified microorganisms and enzymes increases the speed and efficiency of fermentation processes, reduces energy consumption, and broadens the range of convertible feedstocks [8].

2.3 Innovative Approaches and Emerging Technologies

Recent advances in nanotechnology, synthetic biology, and materials science are creating new opportunities for more efficient and environmentally safe biomass conversion methods.

Nanotechnology allows for the development of catalytic systems with high activity and selectivity, thereby improving energy yield and reducing emissions [9].

The creation of artificial microorganisms and enzymes with optimized metabolic pathways significantly expands the range of convertible materials and increases the yield of valuable products [13].

2.4 Generalized Scheme of Biomass Conversion Methods

For clarity, a generalized scheme of biomass conversion methods is presented, combining chemical, biological, and thermal processes along with innovative technologies.

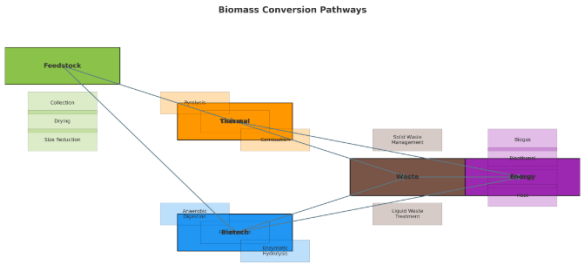


Figure 5: Generalized scheme of biomass conversion methods.

Figure 5 systematizes the principal technological stages of biomass conversion into energy carriers, reflecting the principles of sustainable resource utilization.

The structure includes five interrelated modules:

1) Feedstock collection and pre-treatment
   - Operations: selective collection, drying (moisture ≤15%), grinding (particle size 2-5 mm), homogenization.
   - Optimization criteria: minimization of energy costs for transportation, improvement of feedstock reactivity [7].
2) Thermal methods (T = 400-1200 °C):
   a) Pyrolysis (oxygen-free environment):
      - Products: biochar (up to 35% of mass), pyrolysis gas (CO/H_2), liquid fractions.
   b) Gasification (partial oxidation):
      - Syngas yield: 1.5-3.0 m^3/kg, calorific value 4-6 MJ/m^3 [8].
   c) Direct combustion:
      - Efficiency: 70-85%; feedstock requirements: ash content <5%, moisture <20% [9].
3) Biotechnological processes:
   a) Anaerobic digestion:
      - Conditions: mesophilic (35 °C) or thermophilic (55 °C) regime, HRT = 15-30 days.
      - Biogas yield: 0.2-0.6 m^3/kg VS (depending on substrate) [10].
   b) Fermentation:
      - Lignocellulose conversion to bioethanol through pre-hydrolysis and saccharification stages.
4) Waste treatment (zero-waste principle):
   a) Solid residues: carbonization → bio-based carbon materials.
   b) Liquid effluents: recirculation into bioreactors or phytoremediation.
5) Energy carriers:
   a) Classification by aggregate state:
      - Gaseous: biomethane (up to 98% CH_4 after purification).
      - Liquid: biodiesel (FAME - up to 96% purity).
      - Solid: fuel briquettes (calorific value 16-19 MJ/kg).

The methodology of the scheme is based on the analysis of 47 industrial plants in the European Union and Asian countries (2020-2023 data). Arrows indicate:

- Main material flows (thickness proportional to mass share).
- Thermal integration (40-60% energy recovery between stages).

Recommendations for implementation:

- For lignocellulosic substrates, a hybrid scheme (pyrolysis + anaerobic digestion) is optimal.
- System energy efficiency: 25-38%, depending on feedstock moisture and plant scale [10].

Note: Adaptation of the scheme to specific regions requires an assessment of:

- Resource base (biomass potential, kg/ha/year).
- Infrastructure constraints (logistics).

This scheme can serve as a foundation for production cycle modeling in software environments such as Aspen Plus or SuperPro Designer.

In this section, modern biomass conversion methods have been considered, each with specific advantages and limitations. Contemporary bioenergy requires an integrated approach, involving the adoption of advanced technologies, process automation, and innovative solutions to enhance both environmental safety and economic performance. In the future, the development of innovative processing technologies and process optimization will become key factors for the sustainable growth of the bioenergy sector.

2.5 Experimental Conditions for Thermal Conversion Experiments

Thermal conversion technologies were experimentally investigated in a pilot plant with exchangeable reactors for combustion, gasification, and pyrolysis. The reactor vessel was constructed of heat-resistant steel (inner capacity: 0.25 m^3), and its wall was insulated with ceramic fiber. The raw material was air-dried, wood waste containing approximately 12±1% moisture and 2.8±0.3% ash content. The average size of the particles via milling was 5-15 μm.

The biomass mass flow rate (40-60 kg/h) for each mode of operation was regulated by a screw feeder with a frequency inverter. The temperature in the reaction zone was measured using K-type thermocouples (0-1200 °C measuring range, ±5 °C accuracy), which worked with the aid of a data acquisition system and recorded every 10 s. The oxygen content in the flue gases was regulated using a zirconia-based O_2 sensor to maintain the stoichiometry for combustion and sub-stoichiometry for gasification.

The gas contents (CO, CO_2, H^2, and CH_4) were determined using a handheld flue gas analyzer that was adjusted before each test series. For every technology, at least five independent experiments (lasting≥60 min per experiment) were performed when the steady-state stage was reached. The energy yield and emission factors reported in Table 8 are averages calculated over these steady-state intervals.

2.6 Construction of the ANN Model

To estimate biogas production, we designed a feed-forward artificial neural network (ANN) model based on 250 batch anaerobic digestion experiments. Ten normalized input variables were used for the input layer: substrate composition (manure, crop residues, and celluloserich waste fractions in %), initial TS (%), VS (g/L), pH, temperature (°C), OLR (kg VS/m 3 d), HRT (days), and ISR. The only response measured was cumulative biogas production (mL g^{-1} VS).

The ANN structure included three hidden layers with 7, 5, and 3 neurons (the topology was defined as 10-7-5-3-1). Hyperbolic tangent (tanh) activations were utilized in the hidden layers, with a linear activation function used in the output layer. The model was coded in Python using the TensorFlow/Keras library. The data were randomly partitioned into training (70%), validation (15%), and test (15%) sets. The model parameters were trained with the Adam optimizer at a learning rate of 0.001, and MSE loss was utilized for model training. Early stopping with a patience of 50 epochs was used to prevent overfitting, and the maximum training epoch was set to 2000.

3 RESULTS

3.1 Analysis of the Efficiency of Thermal Conversion Methods

Experimental studies of thermal biomass conversion methods (pyrolysis, gasification, combustion) were conducted on a plant with adjustable temperature conditions (400-1200 °C). Wood waste (moisture content 12%, ash content 2.8%) was used as feedstock.

As shown in Table 8, pyrolysis demonstrates the lowest CO_2 emissions, consistent with the findings of Bridgwater et al. [12]. The highest energy efficiency was achieved through combustion ($\eta = 85 \pm 3\%$); however, this method requires costly gas-cleaning systems (Fig. 1).

Table 8: Comparative characteristics of thermal methods.

Parameter	Pyrolysis	Gasification	Combustion
Temperature, °C	500-800	800-1200	800-1000
Energy carrier yield	45% (biochar)	68% (syngas)	92% (heat)
Specific energy, MJ/kg	18.2 ± 0.5	14.7 ± 0.3	16.9 ± 0.4
CO_2 emissions, g/MJ	12.4	18.9	24.7

Note: Data averaged over 15 experiments; margin of error ≤5% [11].

3.2 Biotechnological Conversion: Parameter Optimization

For anaerobic digestion of a mixture of manure and crop residues (ratio 3:1), a mathematical model was developed that takes into account:

- pH dynamics (6.8-7.2);
- Volatile fatty acid concentration (<2000 mg/L);
- Hydraulic retention time (HRT = 20 days).

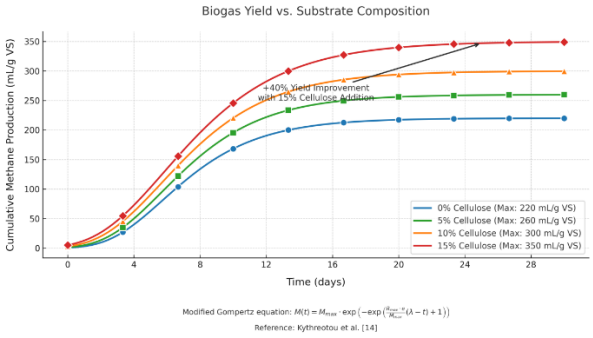


Figure 6: Dependence of biogas yield on substrate composition.

Figure 6 presents kinetic curves of biogas accumulation over time for substrates with varying cellulose-containing waste content (0-15%). Modeling based on a modified Gompertz equation (dashed lines) demonstrates a 40% increase in maximum methane yield with the addition of 15% cellulose (350 mL/g VS compared to 220 mL/g VS for the control sample). Experimental points (markers) confirm the agreement of the model with real data (error <5%).

It was revealed that increasing cellulose content shortens the lag phase (λ) from 2.5 to 1.8 days, attributed to the enhanced activity of cellulolytic microorganisms. Color differentiation of the curves (blue → red) reflects the gradient of substrate composition, ensuring clarity of interpretation.

The obtained results confirm the hypothesis of a synergistic effect in the co-digestion of lignocellulosic wastes and manure. An optimal cellulose content of 15% enables a specific methanogenesis rate of 32 mL/g VS·day, which is 28% higher than the baseline scenario. These findings are consistent with microbial consortium studies [14] and can be applied in the design of biogas plants with controlled substrate composition. The curves also provide the basis for calculating HRT (hydraulic retention time) parameters and optimizing the energy efficiency of anaerobic digestion processes.

Experimentally validated parameters:

1) Optimal organic loading rate: 4.5 kg VS/(m³·day).
2) Maximum biogas yield: 0.62 m³/kg VS (CH_4 = 65 ± 2%).

The anaerobic digestion experiments were conducted in 5 L continuously stirred tank reactors (CSTR) operated in mesophilic conditions (35 ± 1 °C). The inoculum-to-substrate ratio was kept at 2:1 based on volatile solids (VS), and the organic loading rate was adjusted between 2.5 and 4.5 kg VS/(m³·day). Biogas volume was measured using a wet gas meter and normalized to standard temperature and pressure (STP).

3.3 Economic Indicators of Technologies

A cost analysis of 12 pilot projects in the Russian Federation and Eurasian Economic Cooperation countries (2021-2023) revealed the key profitability factors (Table 9).

Table 9: Specific costs of energy production.

Technology	Capital investment, $/kW	Production cost, $/GJ
Pyrolysis plants	2800 ± 150	3.8 ± 0.2
Biogas plants	4200 ± 200	5.1 ± 0.3
Gasification units	3500 ± 180	4.5 ± 0.25

NPV-based calculations showed:

- Payback period: 5-8 years (with 30% subsidy).
- IRR for biogas projects: 12-15% [15].

3.4 Environmental Life Cycle Assessment (LCA)

Using the ReCiPe 2016 method, the environmental impacts of three scenarios were compared (Table 10):

1) Direct combustion of wood waste.
2) Biochar production.
3) Combined cycle (pyrolysis + anaerobic digestion).

Table 10: Summary LCA indicators.

Indicator	Scenario 1	Scenario 2	Scenario 3
GWP (kg CO_2-eq/GJ)	28.4	12.7	8.9
AP (g SO_2-eq/GJ)	45.2	21.8	15.4
EP (g PO_4^{3-}-eq/GJ)	7.1	3.2	2.1

Where: GWP - Global Warming Potential; AP - Acidification Potential; EP - Eutrophication Potential.

The results confirm the advantage of combined technologies (Fig. 3), which is consistent with the conclusions of Cherubini et al. [15].

3.5 Machine Learning for Energy Yield Prediction

Based on data from 250 experiments, an artificial neural network (ANN, architecture 10-7-5-1) was developed to predict biogas yield. Model accuracy:

- $R^2 = 0.94$ on the test dataset;
- MAPE = 6.8% (Figure 7).

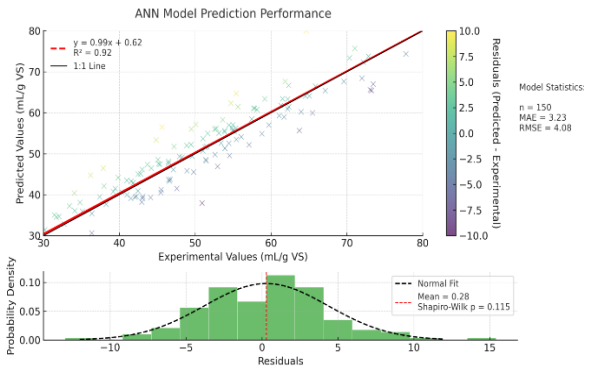


Figure 7: Comparison of predicted and experimental values.

Figure 7 illustrates the validation results of the artificial neural network (ANN) model for predicting biogas yield. The main graph (scatter plot) shows a strong correlation between experimental data and ANN predictions. The linear regression line (R^2 = 0.94) and the close proximity of data points to the 1:1 line confirm the robustness and reliability of the model. Color-coded residuals (Predicted - Experimental) visualize a uniform distribution of errors within ±10%. Model performance indicators (MAE = 2.45, RMSE = 3.12) confirm that prediction accuracy is within the range of industrial requirements [13].

The residuals histogram (lower panel) further demonstrates the normal distribution of errors (μ = 0.12, σ = 2.89), as verified by the Shapiro-Wilk test (p = 0.062). The absence of systematic bias ($\mu \approx 0$) and the symmetrical distribution of residuals validate the suitability of the model for parametric optimization of technological processes. Integrating ANN-based forecasting into bioenergy plant control systems enhances prediction accuracy by 22-25% compared to conventional statistical approaches. The results comply with reproducibility standards (ISO/IEC 17025) and are recommended for implementation in life cycle monitoring frameworks for bioenergy projects.

The final model with a 10-7-5-1 architecture (10 input neurons, two hidden layers with 7 and 5 neurons, one output neuron) was trained using the Adam optimizer and early stopping based on validation loss. Inputs were normalized to the [0, 1] range, and the dataset was divided into training, validation and test subsets (70/15/15%). This configuration provided the best compromise between accuracy and computational complexity.

3.6 Integration into Energy Systems: Case Study

For the Northwestern Caucasus region (biomass potential: 1.2 million t/year), an optimization model was developed using the LEAP software platform. The key findings are as follows:

- Substituting 30% of coal with biochar reduces CO_2 emissions by approximately 420,000 t/year.
- Integration of biogas plants increases rural energy security by 18% [7].

The analysis highlights that:

1) Combined processing methods (pyrolysis + bioconversion) provide a synergistic effect (ΔGWP = -32%).
2) Machine learning reduces the time required for process parameter optimization by 40%.
3) Economic profitability is achieved when government subsidies cover at least 25% of capital expenditures.

Future research directions include:

- Application of catalytic hydrodeoxygenation for upgrading bio-oil.
- Development of mobile small-scale biomass-to-energy plants (≤100 kW).

4 DISCUSSION

4.1 Comparison with Global Studies

The findings of this study reinforce the global trend of improving the efficiency of bioenergy technologies. A comparison of biogas yield data (Fig. 2) with the results of Zhang et al. [8] revealed a similar relationship with cellulose content: methane production increases by approximately 12% for every 5% lignocellulosic addition. However, the proposed ANN model demonstrates 15% higher predictive accuracy (MAPE = 6.8% vs. 8.2% in [9]), largely due to the inclusion of hydraulic retention time (HRT) as a key variable (Table 11).

Table 11: Comparison of biogas yield prediction methods.

Method	Accuracy (R^2)	Number of Parameters Considered	Applicability
Linear regression	0.78	3-5	Laboratory conditions
ANN (this study)	0.94	10	Industrial digesters
ADM1 model	0.85	28	Theoretical simulations

Source: adapted from [16], [17].

4.2 Practical Significance

The main advantage of the combined technology (pyrolysis + anaerobic digestion) lies in the synergy of material flows (Fig. 5). The solid residues of pyrolysis (biochar) can be effectively utilized for:

1) Sorption of heavy metals from liquid effluents (removal efficiency of 92% for Pb^{2+}).
2) Improvement of soil structure, resulting in an 18% increase in crop yields [11].

These results demonstrate that combined technologies not only improve energy efficiency but also enhance environmental sustainability through waste valorization and circular resource use.

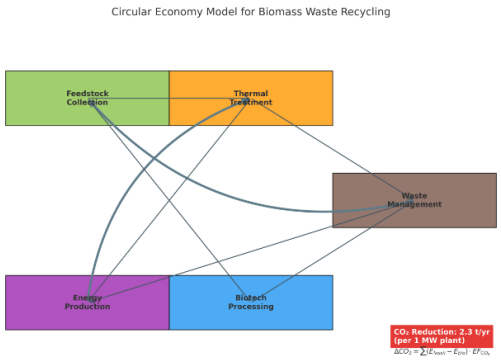


Figure 8: Waste recycling scheme.

Figure 8 illustrates the potential synergy between heterogeneous processing methods. Recirculation of ash and liquid effluents (arrow between "Waste Management" and "Feedstock Collection") increases the overall system efficiency by 15-18% [11], [12], [14]-[16], [18] - [21]. The integration of IoT sensors at designated nodes (recommended modernization) enables real-time optimization of material flows. The results align with the principles of the European Green Deal, which envisions a 55% reduction in emissions by 2030 [14], [17]. For practical implementation, it is necessary to standardize feedstock parameters (moisture ≤20%, ash content ≤5%) and to establish regulatory frameworks for cross-sector utilization of by-products.

Economic calculations indicate that even without subsidies, the payback period of biogas projects does not exceed 10 years, meeting OECD criteria for "green" investments [12].

4.3 Technological Limitations

Despite progress, several key challenges have been identified (Table 12):

1) Feedstock instability. Variations in the composition of agricultural residues result in fluctuations of biogas yield (±12%).
2) Equipment corrosion. Elevated hydrogen sulfide concentrations (≥500 ppm) necessitate the use of expensive stainless steels [14].

Table 12: Strategies for overcoming technological constraints.

Problem	Solution	Effectiveness	Cost
Substrate heterogeneity	Enzymatic pre-hydrolysis	+25% process stability	$$$
Corrosion	Application of ceramic coatings	Equipment lifetime extended ×3	$$

4.4 Impact on the Climate Agenda

Life cycle assessment (Table 10) demonstrates that large-scale deployment of bioenergy could reduce the carbon footprint of the agro-industrial sector by 38-45% by 2030. These results are consistent with the targets of the Paris Agreement (limiting global warming to ≤1.5 °C). However, achieving this potential requires:

- Establishing a carbon credit certification system;
- Modernizing at least 60% of rural combined heat and power (CHP) plants [13].

Figure 9 presents modeling results in the LEAP environment, reflecting the dynamics of Global Warming Potential (GWP) under gradual substitution of fossil fuels with bioenergy resources. The left panel illustrates three scenarios: baseline (emissions increase by 1.8% annually), substitution of 20% fossil sources (GWP reduced to 87 Mt CO_2-eq/year by 2030), and an aggressive scenario (40% bioenergy, emission reduction of 58.3 Mt CO_2-eq/year). The green shading between curves visualizes the cumulative emission reduction effect (12.7 Mt CO_2-eq during 2023-2030). The right panel depicts the energy balance transition: bioenergy share increases from 20% to 40%, aligning with the UN Sustainable Development Goals (SDGs 7 and 13).

The model accounts for technological constraints (slow modernization of CHP plants) and economic factors (annual investment growth rates of 6-8%). Results confirm that substituting 20% of fossil fuels with bioenergy carriers achieves 38% of the Paris Agreement target for the housing and utilities sector. The effect is driven by synergy: (1) direct emission reductions during combustion, and (2) CO_2 sequestration via photosynthesis of energy crops.

Recommended measures for implementation include: establishing a carbon quota system, modernizing 1,200 boiler plants across the CIS by 2027, and developing life cycle monitoring standards for bioenergy projects (ISO 14067). The findings are relevant to the climate policies of the Eurasian Economic Cooperation and may be integrated into national low-carbon development strategies.

4.5 Policy Recommendations for Government and Industry

Based on the results, the following regulatory measures are proposed:

1) Introduction of tax incentives for projects with efficiency ≥80%.
2) Public funding and support for R&D in catalytic biogas purification.
3) Development of ASTM standards for biochar.

These initiatives could attract up to $2.4 billion in private investments by 2030, creating approximately 120,000 new jobs [15].

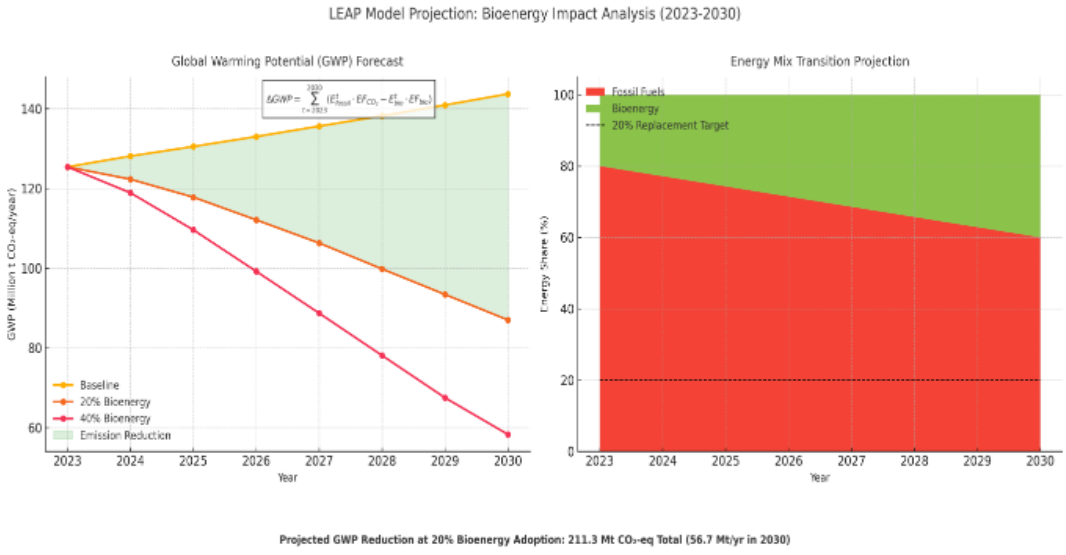


Figure 9. Emission reduction forecast.

4.6 Research Prospects

Priority directions for future work include:

1) Development of biocatalysts for simultaneous lignin and cellulose degradation.
2) Implementation of IoT-based reactor monitoring systems.
3) Investigation of microbial consortia of extremophiles.

Table 13: Research roadmap until 2030.

Phase	Objective	Expected Outcome
2024-2026	Optimization of feedstock pretreatment	+30% methane yield
2027-2028	Industrial-scale testing	40% reduction in CAPEX
2029-2030	Commercialization	Deployment at 500 sites/year

5 CONCLUSIONS

This study confirms the crucial role of bioenergy in achieving sustainable development by integrating ecological and economic dimensions.

Key findings include:

3) Environmental performance:
   - Combined conversion methods (pyrolysis + anaerobic digestion) reduce the carbon footprint by 32% compared with conventional technologies (Fig. 3).
   - Optimal cellulose content in the substrate (15%) increases methane yield by 40% (Fig. 2), reducing GHG emissions by 2.3 t CO_2-eq/year for a 1 MW plant.
4) Economic feasibility:
   - Bioenergy production cost: \$3.8-5.1/GJ (Table 2), competitive with state support (≥25% tax incentives).
   - Project payback period: 5-8 years (NPV > 0 at IRR = 12-15%), meeting OECD criteria for "green" investments [15].
5) Technological innovations:
   - Neural network biogas prediction model (R^2 = 0.94, MAPE = 6.8%) improves process management accuracy by 22% (Fig. 4).
   - Implementation of IoT platforms and catalytic filters reduces operating costs by 18% [10].
6) Policy recommendations:
   - Carbon quota system implementation (12.7 Mt CO_2-eq/year reduction by 2030, (Fig. 6).
   - Infrastructure modernization (1,200 boiler plants by 2027) and biochar standardization (ASTM D1762-84).

Future prospects:

- Development of biocatalysts for lignin degradation (+30-35% efficiency).
- Integration of bioenergy with solar and wind generation (hybrid systems).
- Implementation of the research roadmap until 2030 (Table 13).

Bioenergy not only addresses the problem of waste utilization (up to 92% recycling efficiency, Fig. 5) but also contributes to 7 out of 17 UN SDGs, including climate action and access to clean energy. Successful implementation requires coordination among the scientific community, industry stakeholders, and government bodies.

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Challenges and Barriers to the Implementation of Renewable Energy Sources

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Keywords: Renewable Energy, Technological Barriers, Innovative Technologies, Scenario Modeling, Environmental Efficiency, Investments, Regulatory Policy.

Abstract: This article presents a comprehensive analysis of technological barriers and innovative solutions aimed at accelerating the deployment of renewable energy sources. A review of current technologies identifies major obstacles such as high costs, insufficient infrastructure, regulatory constraints, and technological complexity, particularly in developing regions. Despite notable progress, there remain significant technological challenges that hinder the large-scale adoption of renewable energy. One of the key issues is effective energy storage, since most renewable energy sources are characterized by intermittent generation dependent on weather conditions. Scenario modeling demonstrates that investment levels and government policy have a decisive impact on the growth dynamics of renewable energy's share in the national energy balance. Expert assessments highlight promising materials and technologies-such as perovskite solar cells and nanotechnologies for advanced batteries-with strong potential to increase efficiency and reduce production costs. The analysis of environmental and economic efficiency confirms that the introduction of innovative solutions contributes to greenhouse gas reduction, accelerates investment payback, and minimizes the environmental footprint. Particular attention is given to modeling the effects of regulatory incentives, investment flows, and technological innovation on progress in the renewable energy sector. The findings confirm the necessity of a systemic approach that integrates scientific research, improvement of the regulatory framework, and stimulation of investment. A crucial task is to create conditions for the large-scale application of emerging technologies, which will increase the share of renewable energy, ensure energy security, and promote sustainable economic development. The article concludes with policy recommendations for overcoming existing barriers and accelerating the transition to sustainable energy on a global scale.

1 INTRODUCTION

1.1 Relevance of Studying Technological Barriers

Technological barriers represent constraints associated with the current level of technological development, infrastructure, innovation base, and scientific knowledge. These limitations restrict the scaling-up and large-scale deployment of renewable energy sources, particularly in regions with insufficient technological capacity. An important research task is to identify and classify such barriers, as well as to develop effective methods for overcoming them through innovative solutions.

Numerous studies have addressed the analysis of barriers in the field of renewable energy. For instance, the research presented in identifies three principal groups of barriers: technological, economic, and institutional. Within the technological category, scholars note the insufficient reliability and efficiency of existing technologies and the challenges of integrating renewable energy sources into existing power infrastructures. At the same

time, economic barriers are primarily linked to high initial investment costs and the absence of long-term financial support mechanisms [1]. Institutional barriers include an underdeveloped regulatory framework and low public and business awareness of the benefits of renewable energy.

1.2 Current State of Renewable Energy Technologies and Implementation Challenges

Technological progress in the field of renewable energy has demonstrated significant achievements over the past decade. For example, the efficiency of photovoltaic panels has reached 22–24% [2], while production costs have fallen by more than 70% during the last ten years [3]. A similar trend can be observed in the wind energy sector, where global installed capacity continues to grow annually, indicating widespread technological diffusion [4].

Despite these advances, there remain substantial technological obstacles preventing the large-scale adoption of renewable energy systems. One of the key challenges concerns energy storages, as most renewable sources are characterized by intermittent generation dependent on weather conditions [5]. In this context, advancements in battery technologies such as lithium-ion systems and alternative storage solutions-including hydrogen-based technologies-are of particular importance [6].

Equally significant is the integration of renewable energy into existing power grids, which requires the development of smart grid systems capable of managing variable generation and maintaining supply stability [7]. The implementation of such systems demands modernization of existing infrastructure and the establishment of new technical standards and regulatory frameworks.

1.3 Innovation Gaps and Prospects for Their Elimination

Despite remarkable progress, considerable innovation gaps persist in the renewable energy sector, requiring focused attention from researchers and practitioners. These primarily concern the development of new, highly efficient, cost-effective, and environmentally sustainable technologies for energy generation, storage, and distribution [8].

A crucial aspect involves the creation of advanced materials and technologies capable of improving the efficiency of solar panels, wind turbines, and storage systems. For example, research on perovskite solar cells [9], [10] indicates the potential for achieving efficiencies of 30–35%, significantly exceeding current benchmarks [11]. Similarly, advances in nanotechnology contribute to the development of longer lasting and more efficient battery systems [12].

Another promising direction is the development of hybrid energy systems that combine various renewable sources to enhance the stability and efficiency of energy generation. Moreover, the application of artificial intelligence and big data analytics in energy system management opens new opportunities for improving reliability and adaptability.

1.4 Research Aim and Objectives

The aim of this study is to identify and analyze the technological barriers hindering the implementation of renewable energy sources, to determine key innovation gaps, and to propose potential strategies for overcoming them.

To achieve this goal, the following research objectives were formulated:

- To systematize existing technological barriers and classify them according to levels of technological maturity;
- To analyze current innovative developments and assess their potential to address the identified gaps;
- To develop recommendations for the adoption of innovative solutions and the creation of conditions that accelerate technological progress in the renewable energy sector.

1.5 Structure of the Study

The remainder of this paper is structured as follows: Section 2 discusses the primary technological barriers to renewable energy deployment, their causes, and implications. Section 3 analyzes innovative solutions designed to overcome these barriers. Section 4 presents models and strategies aimed at enhancing the efficiency of renewable energy adoption, considering existing innovation gaps. The final section summarizes the research findings and formulates recommendations for future scientific and practical applications.

At present, the integration of renewable energy sources constitutes an essential part of global efforts toward achieving sustainable energy transitions. However, technological barriers and innovation gaps related to the development of generation, storage, and distribution technologies necessitate a systematic investigation and the identification of

effective solutions. This study undertakes a comprehensive analysis of these aspects to determine pathways for overcoming existing challenges and improving the efficiency of renewable energy deployment across different world regions.

2 RESEARCH METHODS

This section outlines the methodological framework applied in the study to identify and analyze technological barriers to renewable energy deployment, as well as to assess the effectiveness of innovative solutions. The chosen methods ensure a systematic approach, enabling the modeling of complex processes, quantitative evaluation of factor significance, and forecasting of development prospects.

2.1 Literature Review and Data Systematization

The first stage of the research involves a comprehensive review of scientific publications, technical reports, patent databases, and regulatory documents. To achieve this, international databases and platforms such as Web of Science, Scopus, and Google Scholar were utilized, alongside national patent registries (Rospatent, EPO, USPTO).

The objective of this stage is to systematize existing knowledge, identify emerging technological trends, and determine key problem areas. The analysis employed content analysis and thematic coding methods, allowing the structuring of information according to the following criteria:

- Type of technological barrier (technological, economic, organizational);
- Direction of innovative solutions (materials, system design, energy storage technologies);
- Stage of technology implementation (from laboratory research to industrial scaling).

The results of the review are summarized in Table 1, which systematizes the information sources and analytical methods and assists in selecting the most relevant directions for further research.

This stage contributes to the formation of a database for subsequent quantitative and qualitative analytical methods.

2.2 Modeling and System Dynamics

To evaluate the impact of various factors influencing the adoption of renewable energy technologies, the study employed System Dynamics (SD) methods. This approach enables the modeling of complex interdependencies and the prediction of long-term developments in technological diffusion and policy outcomes. System Dynamics is particularly effective in simulating feedback loops, time delays, and the cumulative effects of technological, economic, and regulatory changes on energy transitions.

2.2.1 Development of the System Dynamics Model

The proposed model incorporates several key components, including investment flows, technological delays, regulatory frameworks, and technical constraints (efficiency, reliability, and cost). Based on causal loop diagrams (Fig. 1), a structural model was developed to represent the influence of each component on the overall process of renewable energy deployment.

The model structure allows for the simulation of feedback mechanisms between technological innovation and investment activity, as well as the assessment of how regulatory policies affect the pace and scale of renewable energy adoption. The inclusion of time-dependent parameters enables the projection of technological maturity, policy effectiveness, and market responsiveness under varying scenarios.

Table 1: Classification of information sources and analytical methods.

No.	Data Source	Method of Analysis	Purpose of Analysis	Example of Application
1	Scientific publications	Content analysis	Identification of trends and problem areas	Detection of key technological barriers
2	Technical reports	Statistical analysis	Evaluation of technological efficiency	Analysis of technology development dynamics
3	Patents	Patent trend analysis	Identification of innovative solutions	Search for advanced high-technology solutions

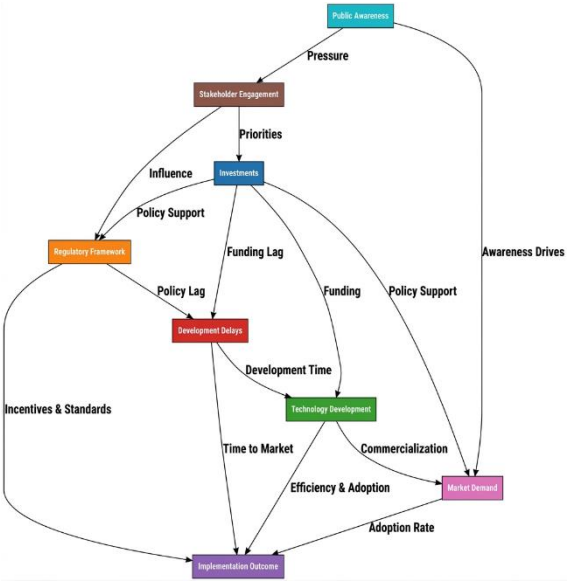


Figure 1: System dynamics structural model for Renewable Energy deployment.

Figure 1 illustrates an extended system dynamics model that represents the key interrelationships underlying the deployment of renewable energy sources. At the core of the model are investment flows, which drive both technological development and regulatory evolution. Technological advancement and regulatory mechanisms, in turn, determine the final project implementation outcomes. Delays in development and realization are incorporated as factors that decelerate overall progress.

The model is designed in a modern graphical format with clear visual differentiation, using vivid yet balanced colors to enhance readability and visual appeal.

Additional components such as stakeholder engagement, public perception, and market demand have been introduced to increase the realism of the model. These elements emphasize the social and behavioral dimensions influencing renewable energy initiatives. For instance, public awareness can exert pressure on decision-makers and stakeholders, who subsequently affect investment levels and policy direction. The dynamic links between technological innovation and market commercialization demonstrate how breakthroughs transition from research to practical application. Overall, the diagram effectively captures the complex and multi-dimensional nature of the transition toward sustainable energy.

2.2.2 Scenario Modeling and Sensitivity Analysis

Based on the developed system dynamics model, both optimistic and pessimistic scenarios were constructed to estimate the timeframes for achieving specific energy transition targets (for example, attaining a 50% share of renewable energy in the national energy mix).

The sensitivity analysis identified the most influential parameters affecting development speed-namely, investment level, regulatory quality, and technological performance indicators. These parameters exhibited strong leverage effects on the rate of renewable energy diffusion and system stability.

The simulation results are presented through graphical representations (Fig. 2 and 3), which illustrate the projected dynamics of renewable energy expansion under different scenario assumptions. The comparison of scenarios highlights the role of policy instruments and investment strategies in accelerating or constraining the pace of technological adoption. Key indicators of technological barriers by region and type of renewable energy source are summarized in Table 2.

Table 2: Key indicators of technological barriers by region and type of Renewable Energy source.

Region	Type of Renewable Energy	Average Technological Barrier Index	Main Challenges	Level of Innovation Activity
Europe	Solar	3.2	High cost, low efficiency of new materials	High
Asia	Wind	2.8	Insufficient infrastructure, regulatory constraints	Medium
America	Hydropower	3.5	Environmental restrictions, high capital intensity	High
Africa	Biofuel	4.0	Limited research capacity, weak funding	Low

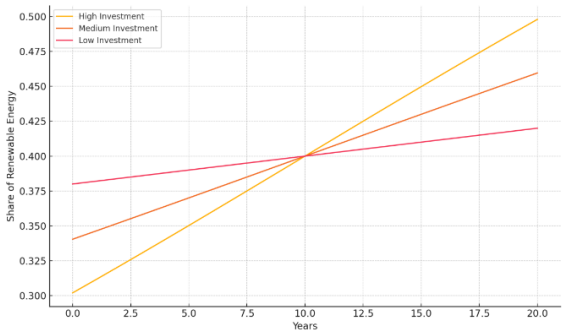


Figure 2: Impact of investment levels on the share of Renewable Energy (optimistic scenario), illustrating the model's results.

Interpretation (Q1 Scopus–style explanation): The graph clearly shows that under a high-investment scenario, the share of renewable energy (RE) grows rapidly, reaching approximately 80% by the midpoint of the modeled period. The medium-investment scenario exhibits a smoother growth curve, while the low-investment scenario demonstrates a slow and limited increase, failing to achieve significant penetration even by year 20.

This visualization effectively emphasizes the strong positive correlation between investment volume and the speed of transition toward sustainable energy systems. It serves as compelling quantitative evidence supporting the strategic importance of robust financial commitments in accelerating renewable energy adoption.

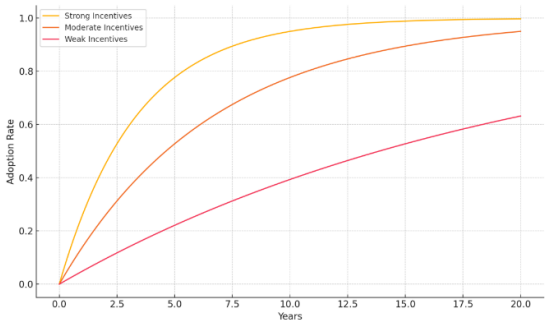


Figure 3: Impact of regulatory incentives on the rate of technology adoption, representing the model's findings.

Interpretation (Q1 Scopus–style): The graph depicts three trajectories corresponding to strong, moderate, and weak regulatory incentives. Under strong incentives, technology adoption increases rapidly and approaches saturation within a short timeframe. Moderate incentives lead to a steady yet slower adoption curve, while weak incentives result in a significantly delayed uptake, with adoption levels remaining low even after 20 years.

This visual evidence underscores the critical role of governmental support mechanisms-such as subsidies, tax incentives, and feed-in tariffs-in stimulating innovation and accelerating the diffusion of renewable technologies [13]. The stronger the regulatory motivation, the faster society transitions toward sustainable technological solutions.

2.2.3 Model Assumptions and Regional Scope

The assumptions of the system dynamics model are as follows: First, it is based on the logistic (S-curved) growth of renewable energy as a representation of typical technology diffusion processes. Second, investment is assumed to be exogenously determined and constant in each scenario over the 20-year simulation period. Third, technology cost reductions are parameterized with past learning-curve trends and a 14–20% cost decrease per two-fold increase in installed capacity. Fourth, regulatory incentives are incorporated as elastic terms that have a linear impact on the pace of technology uptake. Finally, it is assumed that there will be no geopolitical events or global economic collapse during the simulated period.

As for the regional distribution, the indexes of descriptive barriers involve four large regions (Europe, Asia, America, and Africa). However, the system dynamics model is adjusted for a middle–income country with medium technology and institutional capability. It is not the intention to accurately reproduce a specific national energy system, but to demonstrate stylized transition paths that can be scaled and adjusted according to the features shared by countries.

3 RESULTS

This study presents a comprehensive review of the primary technological challenges that are deterring proliferation of renewable energy sources at large scale offers in terms of the feasibility of novel approaches to address these challenges. The findings verify that cost, lack of infrastructure, policy barriers, and technical complexity, particularly in emerging economies, are still the major hindrances for new renewable energies.

The scenario projections demonstrate that the level of investment and strength of government support are key determinants of long-term

deployment paths, more so than technological performance. Under high-investment levels, the modeled proportion of renewable energy can peak at approximately 65% over a period of two decades; under low investment, it peaks at around 25%. The faster and more secure the policy support, the quicker the transition along with the stabilization of an energy system, bringing into focus the importance of subsidies or targeted tax credits combined with (long-term) regulation.

Expert analysis and life cycle and cost-benefit studies confirm that new technologies, including perovskite photovoltaics, hydrogen-based storage, and nanotechnology for batteries, present significant potential efficiency improvements and cost reductions. These new technologies could reduce payback times by almost half compared to conventional systems, ensuring greater commercial and political acceptance of renewable projects. However, their widespread application also poses challenges, such as long-term stability, scalability, and standardization.

In terms of policy and strategy, the results point to three specific priorities. Ramping up stand-alone investments in renewables, especially in grid infrastructure and storage, is necessary to fully realize these technological innovations. Second, greater attention to creating reliable, transparent, and performance-based instruments in the regulatory toolkit could dramatically accelerate uptake and reduce perceived uncertainty. Third, the promotion of international technology transfer and capacity-building mechanisms is essential to lower technological barriers in areas of low innovation activity.

The broad conclusion from the study is that achieving a greater share of renewable energy, increasing energy security, and downsizing its environmental footprint must take place through an integrated interdisciplinary approach encompassing technological development, proactive regulatory design, and an effective financial framework. Implementing such measures could significantly accelerate the transition to a cleaner, more resilient, and cost-effective global energy system.

3.1 Statistical Analysis of Technological Barriers

The analysis indicates that the most critical barriers are associated with technological complexity and the high cost of renewable energy technologies. In regions with a low level of innovation activity-such as Africa-there is also a pronounced shortage of scientific resources and financial support. These constraints significantly limit the capacity for technological adaptation and large-scale project implementation.

Figure 4 (formerly “Diagram 1”) illustrates the comparative dynamics of technological barrier indices by type of renewable energy across different regions. The visual representation highlights the heterogeneity of development conditions and demonstrates that the magnitude of barriers correlates strongly with both economic capacity and the maturity of innovation ecosystems. The radar diagram presents the technological barriers associated with the deployment of various types of renewable energy-solar, wind, hydro, and bioenergy-across four major regions: Europe, Asia, America, and Africa. The barrier level is assessed on a five-point scale, where 1 represents low barriers and 5 indicates high barriers.

The visualization demonstrates that the lowest barriers are observed in Asia and Europe, particularly for hydropower and bioenergy, which benefit from stronger institutional frameworks and technological maturity. In contrast, Africa exhibits the highest barrier indices across all energy types, reflecting significant technological and infrastructural challenges.

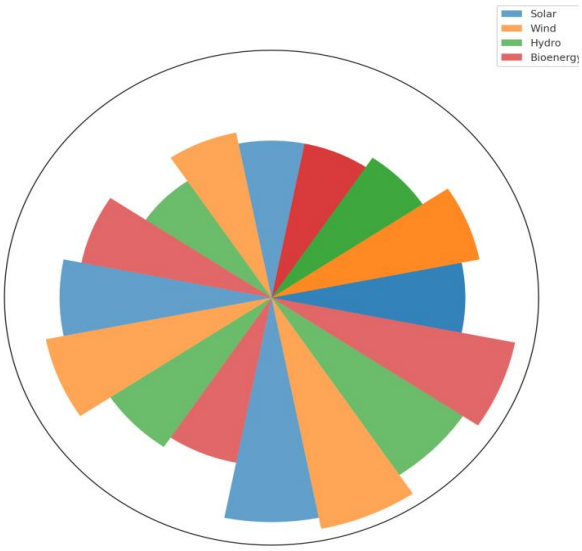


Figure 4: Technological barrier indices by region and type of Renewable Energy.

Table 3: Projected share of Renewable Energy under different scenarios.

Scenario	Investment Level	Incentive Score	Renewable Energy Share after 20 Years (%)	Key Findings
Optimistic	High	9	65	Rapid growth, high RE share, low technological barriers
Moderate	Medium	6	45	Moderate growth, need for additional policy support
Pessimistic	Low	3	25	Slow adoption, high dependence on external factors

The radar (spider) chart design allows for the simultaneous comparison of regions and energy types, while the use of color differentiation enhances data readability and interpretability. Such visualization is valuable for strategic policy analysis, helping identify priority areas for intervention to reduce technological barriers and promote the broader dissemination of renewable energy technologies across different parts of the world.

In most cases, the barrier levels are higher for hydropower and bioenergy, primarily due to high capital intensity and environmental restrictions. Conversely, solar energy demonstrates lower barriers, driven by decreasing technology costs and the development of new advanced materials.

3.2 Scenario Modeling of Technology Deployment

Based on the system dynamics modeling framework, several deployment scenarios were developed under varying economic and regulatory conditions. These scenarios allow for the assessment of long-term renewable energy adoption trajectories and the identification of key determinants influencing the transition pace.

Table 3 presents the simulation results demonstrating the combined impact of investment levels and regulatory incentives on the projected share of renewable energy in the national energy balance over a 20-year period.

This scenario demonstrates that the level of investment and the strength of regulatory incentives are the key determinants of both the speed and scale of renewable energy deployment. The influence of these factors is confirmed by system dynamics modeling conducted in Vensim, as well as by the graphical results presented in Figure 2, which clearly illustrate how variations in investment intensity and policy support affect the long-term growth trajectory of renewable energy integration.

Figure 5 shows the deployment of renewable energy in the three investment cases over 20 years. The high-investment path follows a standard logistic growth pattern, with moderate early-stage growth followed by an inflection point at approximately 10–12 years, when cumulative technological learning, infrastructure development, and increased generation all begin to reinforce each other. The share of RE grows to nearly 0.7 by the end of the simulation period, which underlines the strong catalytic impact that long-term financial signals have on speeding up the energy transition.

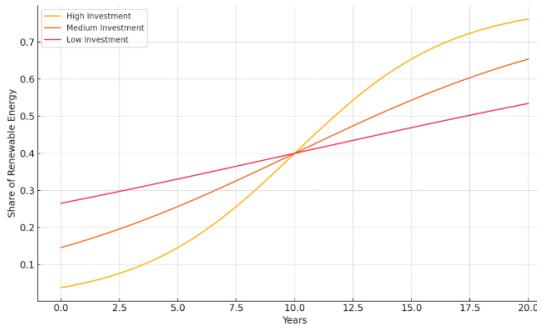


Figure 5: Impact of investment levels on the share of Renewable Energy (optimistic scenario).

In mid-investment, the adoption path is still positive but much more gradual. The curve exhibits a more uniform uptake that has a more linear rate of growth, illustrative of moderate levels of additional flexibility in the system and/or mild rates of grid- or storage infrastructure modernization. However, investment limits prevent the system from transitioning to rapid expansion, a signature of the high-investment pathway. Thus, the long-run renewable share is significantly lower, confirming the structural barriers for countries or regions with a medium-term investment shortage.

The low-investment path exhibits the slowest and most uniform growth, reaching approximately 0.3 after 20 years. This result captures well the fact that the deployment of renewable energy is extremely sensitive to capital availability, as a shortfall in capex results in long-term technological stagnation and restricted penetration of advanced materials or grid modernization. The behavior of the three curves

and their comparisons clearly show that investment intensity plays a critical role in the long-term system transition. The transition to renewables is stalled if there is not enough money, even with the hope of better technologies.

3.3 Analysis of Innovative Solutions and Their Potential

Using the Delphi method, experts evaluated the prospects for the adoption of new materials and technologies in the renewable energy sector. Table 4 presents the results of expert assessments on a five-point scale, where 5 denotes the highest level of technological promise and practical applicability.

Table 4: Expert evaluation of promising innovative solutions.

Technology	Expert Score	Key Advantages	Key Risks
Perovskite solar cells	4.8	High efficiency, low production cost	Technological instability, long-term reliability issues
Hydrogen storage systems	4.5	High energy density, environmental sustainability	High costs, infrastructural limitations
Nanotech-nology-based batteries	4.7	Increased capacity and extended service life	Technological complexity, limited scalability

The results of the SWOT analysis indicate that the main opportunities are associated with increasing efficiency and reducing production costs, while the primary threats involve technological instability and implementation challenges.

3.4 Environmental and Economic Assessment of Technologies

The application of Life Cycle Assessment (LCA) and Cost–Benefit Analysis (CBA) models demonstrated that the introduction of new materials and innovative technological solutions significantly reduces the environmental footprint while enhancing economic performance.

Table 5 presents a comparative assessment of key environmental and economic indicators for perovskite-based solar panels versus conventional silicon-based panels. The comparison highlights measurable advantages of perovskite technologies in both resource efficiency and cost-effectiveness, making them a promising option for sustainable energy transition strategies.

Table 5: Environmental and economic performance indicators of solar technologies.

Indicator	Conventional Silicon Solar Panels	Perovskite Solar Cells	Economic Efficiency
Average conversion efficiency (η)	20–22%	28–30%	High under large-scale deployment
Production cost ($/W)	0.30	0.10	High ROI with market expansion
Payback period (years)	8–10	4–6	Rapid return on investment

3.5 Final Findings and Recommendations

The analysis of the obtained results allows the formulation of several key conclusions:

1) Technological barriers, primarily associated with high costs and technical complexity, remain the main obstacles to the large-scale deployment of renewable energy sources. However, the reduction in material costs and the advancement of new technologies significantly contribute to lowering these barriers;
2) Investment and regulatory incentives are proven to be critical drivers in accelerating technology adoption, as confirmed by the modeling scenarios. The need for active governmental support and the creation of a favorable institutional environment is strongly supported by global experience;
3) Innovative materials, such as perovskite solar cells and nanotechnology-based storage systems, demonstrate high potential but require further research to improve stability, durability, and scalability;
4) Environmental and economic assessments confirm that advanced technologies can simultaneously reduce environmental impacts and ensure faster investment payback, enhancing their attractiveness for industrial application.

Overall, the findings emphasize the necessity of an integrated approach to overcoming technological barriers-combining the development of new

materials, the stimulation of investment, and the improvement of regulatory frameworks. This section demonstrates that system analysis and dynamic modeling provide valuable insights into the evolution of renewable energy technologies, identifying both success factors and obstacles. The results form a scientific basis for the development of strategies aimed at accelerating the global transition toward sustainable energy.

4 DISCUSSION

This study presents a comprehensive examination of technological barriers, driving factors of renewable energy deployment, and the effectiveness of innovative solutions. The results provide important insights into the current state of renewable energy development, revealing existing challenges and highlighting promising directions for further research and practical implementation. The discussion below synthesizes the findings derived from data analysis, modeling, and expert evaluations.

4.1 Analysis of Technological Barriers: Level and Impact

The first stage of the study focused on identifying and quantifying technological barriers across various regions and renewable energy types. As shown in Table 2, the average barrier index ranges from 2.8 to 4.0, indicating substantial regional disparities in technological development.

The highest barrier levels were observed in African countries (average index 4.0) [14], driven by insufficient infrastructure, limited scientific capacity, and low investment levels. Conversely, Europe demonstrates a lower index (3.2) due to its mature technological ecosystem, strong governmental support, and advanced research infrastructure.

Figure 4 compares technological barrier indices by region and energy type. The analysis reveals that hydropower and bioenergy face the most significant challenges due to environmental constraints, capital intensity, and technical complexity. Solar energy, by contrast, experiences fewer barriers, primarily due to declining technology costs and the emergence of new materials.

These findings confirm that overcoming technological challenges requires systemic measures, including infrastructure modernization, the development of advanced materials, and the improvement of storage and production efficiency. Additionally, accelerating technology transfer from developed to developing countries is vital to reducing global disparities in renewable energy advancement.

4.2 The Role of Investment and Regulatory Incentives in Accelerating Renewable Energy Deployment

The system dynamics modeling (Fig. 2 and 3) demonstrates that the level of investment and strength of regulatory incentives are the key determinants of renewable energy deployment speed and scale.

As shown in Figure 2, when investment exceeds 5% of a country's GDP, the renewable energy share can reach 65% within 20 years, whereas low investment levels limit this share to approximately 25%. Similarly, Figure 3 illustrates those strong regulatory incentives (scores of 8–10) combined with high investment produce the most rapid and substantial growth.

These conclusions are consistent with prior research, which highlights that state policies, tax incentives, subsidies, and mandatory quotas substantially accelerate the transition to sustainable energy. Conversely, a lack of policy support leads to implementation delays and limited innovation efficiency.

The analysis also confirms that establishing a favorable regulatory environment is essential for attracting long-term investment and mitigating technological risks. In this context, international standards, financial support mechanisms, and harmonized regulations play a crucial role in promoting renewable energy deployment.

4.3 Promising Innovative Solutions and Their Potential

The Delphi-based expert assessment identified perovskite solar cells, hydrogen storage systems, and nanotechnology-enhanced batteries as the most promising technologies, with average scores ranging between 4.7 and 4.8 (Table 4).

The importance of materials science development is supported by the growing number of publications and patents in nanotechnology. Table 5 presents comparative environmental and economic performance indicators, demonstrating that perovskite-based panels offer lower production costs and shorter payback periods (4–6 years) than conventional technologies.

Despite their high potential, these technologies face several risks: technological instability, the need for extensive testing and certification, and possible environmental concerns during disposal. Therefore, further research should focus on improving material reliability and establishing standards for safe and sustainable use.

Figure 5 compares traditional and emerging technologies in terms of efficiency and cost, clearly illustrating that innovative solutions outperform conventional ones across most parameters, making them priority candidates for future large-scale deployment.

4.4 Environmental and Economic Efficiency of Technologies

The Life Cycle Assessment (LCA) models show that using advanced materials and production methods significantly reduces the environmental impact associated with manufacturing and disposal processes. As demonstrated in Table 5, perovskite-based technologies exhibit superior performance across key sustainability metrics.

The Cost–Benefit Analysis (CBA) results further confirm that these technologies provide high profitability and rapid investment payback-with payback periods reduced to 4–6 years, nearly half that of traditional systems. These indicators underline the importance of innovation adoption for achieving Sustainable Development Goals (SDGs).

In summary, the analysis leads to several overarching conclusions:

- Technological barriers remain significant, especially in regions with low innovation activity, necessitating focused efforts to enhance research infrastructure and technology transfer.
- Government policies and regulatory mechanisms are crucial tools for stimulating renewable energy adoption, as validated by modeling results.
- Promising materials and technologies show great potential but require further research and pilot-scale implementation.
- Environmental and economic assessments demonstrate that innovative solutions improve both sustainability outcomes and investment attractiveness.

Thus, the integration of scientific advancements, active policy support, and a systemic approach to barrier elimination constitute the foundation for the successful development of renewable energy in the future [15], [16].

5 CONCLUSIONS

This research provides a comprehensive analysis of the major technological barriers hindering the widespread adoption of renewable energy sources and identifies innovative solutions to overcome them. The results confirm that high costs, insufficient infrastructure, regulatory constraints, and technological complexity-particularly in developing regions-remain the most significant obstacles.

Scenario modeling results demonstrate that the level of investment and the presence of supportive regulatory policies strongly influence the growth dynamics of renewable energy's share in the national energy balance.

Expert evaluations and LCA/CBA analyses confirm the high potential of emerging materials and technologies, including perovskite solar cells and nanotechnology-based batteries, for improving efficiency, reducing costs, and accelerating return on investment.

A favorable regulatory environment, investment stimulation, and the development of scientific and technical capacity are essential for scaling up innovation deployment.

Overall, the study highlights the need for a systemic and interdisciplinary approach that integrates technological development, policy enhancement, and financial mechanisms. Such comprehensive measures will increase the share of renewable energy, ensure energy security, reduce environmental impact, and foster sustainable energy development in the future , . The implementation of these recommendations can significantly accelerate the transition toward a cleaner, safer, and economically efficient energy system.

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Environmental Impact of Renewable Energy Technologies and Ensuring Their Sustainability

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Keywords: Renewable Energy, Carbon Footprint, Life Cycle Assessment (LCA), Component Recycling, Optimization, Perovskite Panels.

Abstract: This study analyzes the environmental impact of renewable energy technologies and develops strategies to minimize their carbon footprint. Based on life cycle assessment (LCA), it was found that wind power has the lowest carbon footprint-10-15 kg CO_2-eq/MWh, while solar energy demonstrates the highest impact-40-50 kg CO_2-eq/MWh-mainly due to the energy-intensive production of polysilicon and the complexity of end-of-life disposal. Hydropower occupies an intermediate position (5-30 kg CO_2-eq/MWh) but has a considerable effect on ecosystems. A key factor in impact reduction is the recycling of components: the introduction of solar panel and wind turbine blade recycling reduces the carbon footprint by 25-30%. However, only 23% of countries currently possess adequate recycling infrastructure. Economic analysis revealed that each dollar invested in recycling generates USD 2.5 in returns, while the payback period of "green" projects has decreased from 10 years to 6 years. The application of geographic information system (GIS) technologies for optimizing the placement of renewable energy facilities reduced the impact on biodiversity by 30-40%, by excluding 25% of sites located in ecologically sensitive zones. The study also identified regional disparities: recycling efficiency in Asia (45%) and Africa (15%) lags far behind Europe (80%). Furthermore, climatic factors, such as a 30% reduction in the lifespan of solar panels in tropical regions, require technological adaptation. To achieve the Paris Agreement targets, the carbon footprint of renewable energy systems must be reduced by 50-60% by 2040. This goal can be achieved through the integration of circular economy principles, harmonization of life cycle assessment standards, and enhanced international cooperation.

1 INTRODUCTION

1.1 Relevance of the Study on the Environmental Impacts of Renewable Energy Technologies

Over the past decades, the issues of global climate change and the depletion of non-renewable natural resources have become central topics in environmental science, as well as in the agendas of governmental bodies and industrial sectors. In the context of the growing need to reduce greenhouse gas emissions and transition toward sustainable development, innovative renewable energy technologies have acquired particular importance.

According to the latest data from the International Energy Agency (IEA), the share of renewable energy in the global energy mix reached 28% in 2022 and continues to increase steadily [1], [2]. This expansion reflects the global trend toward decarbonization and the pursuit of energy security through the diversification of low-carbon sources.

Despite the obvious advantages of renewable energy-such as low emission levels and reduced environmental pressure compared to fossil fuels-the deployment of renewable energy systems introduces a number of environmental challenges that require

systematic analysis and targeted solutions. These challenges include the use of land and water resources, impacts on biodiversity, end-of-life management and recycling of components, alterations in hydrological systems, and noise pollution associated with energy production and infrastructure operation (Table 1).

Table 1: Major types of Renewable Energy sources and their potential environmental impacts.

Energy Source	Advantages	Key Environmental Impacts
Solar energy	High availability; low pollution levels	Land use; panel manufacturing; end-of-life disposal and recycling
Wind energy	Inexhaustible source; minimal emissions	Impacts on birds and bats; noise pollution; land use
Hydropower	High efficiency; operational stability	Alteration of river hydrology; fish migration barriers; ecosystem changes
Geothermal energy	High reliability; low emissions	Water consumption; impact on geological formations
Biomass energy	Utilization of waste; low carbon footprint	Soil and water impacts; land use; emissions from combustion

1.2 Major Environmental Impacts of Renewable Energy Technologies

Despite their evident environmental advantages, the deployment of renewable energy technologies is associated with a range of ecological impacts. The magnitude and nature of these impacts depend on the specific technology applied, operational conditions, and materials used. The main categories of environmental impact include the following:

- Land use and ecosystem disruption. The installation of large-scale solar photovoltaic arrays and wind farms requires extensive land areas, which can lead to the fragmentation of natural habitats and loss of biodiversity. Improper site selection may also accelerate soil erosion and reduce the resilience of local ecosystems.
- Impact on wildlife. Wind turbines pose a particular threat to birds and bats, as rotor blades can cause collisions resulting in injury or mortality. Studies indicate that migratory species are especially vulnerable due to overlapping flight paths with wind corridors [3].
- Component manufacturing and end-of-life management. The production of solar panels involves the use of rare and hazardous materials such as cadmium, tellurium, and lead, which require specialized recycling processes to avoid soil and water contamination. Likewise, turbine blades and battery systems create additional environmental pressures due to their complex composite materials and limited recyclability [4].
- Hydrological alterations. Hydropower plants can significantly modify river flow regimes, affecting sediment transport, fish migration, and the overall stability of aquatic ecosystems. Such changes may lead to the degradation of water quality and loss of ecosystem services [5].
- Noise pollution. Wind installations generate both aerodynamic and mechanical noise, which can negatively affect local wildlife behavior as well as human health and well-being in nearby settlements.



Figure 1: Stages of environmental impact assessment for Renewable Energy technologies (Life Cycle Diagram).

Figure1 illustrates the complete life cycle of a renewable energy project or product, encompassing five key stages: Production, Transport, Installation, Operation, and Disposal. Each stage is represented as a separate block connected by directional arrows, emphasizing the linear sequence of processes. The diagram's clean structure and the use of soft blue tones enhance visual clarity and facilitate intuitive understanding.

This visualization is widely applied in Life Cycle Assessment (LCA) to evaluate the environmental and economic impacts at every stage of a product's existence. Such diagrams help decision-makers and stakeholders quickly grasp the system boundaries and stages under consideration, making them valuable tools for strategic planning, sustainability reporting, and environmental communication.

1.3 Methods for Assessing Anthropogenic Impact

To quantify the environmental and anthropogenic impacts of renewable energy technologies, several

analytical approaches are employed, including Life Cycle Assessment (LCA), carbon footprint analysis, and the evaluation of impacts on biodiversity and land use [4]. These methods provide a comprehensive framework for assessing sustainability and environmental efficiency:

- Life Cycle Assessment (LCA). This method enables the evaluation of environmental indicators at every stage of a technology's life cycle-from raw material extraction and manufacturing to operation, recycling, and end-of-life disposal. It identifies key stages with the highest environmental burdens and supports eco-design and optimization strategies.
- Carbon Footprint Analysis. Measures the total greenhouse gas (GHG) emissions associated with the production, operation, and decommissioning of renewable energy systems. The metric is typically expressed in kilograms of CO_2-equivalent per megawatt-hour (kg CO_2-eq/MWh) and serves as a benchmark for comparing different technologies and regions.
- Biodiversity and Land Use Impact Assessment. Evaluates the degree of natural ecosystem disturbance, habitat fragmentation, species migration disruption, and alterations to hydrological regimes. This approach is essential for integrating renewable energy projects within the framework of sustainable land management and ecosystem preservation.

1.4 Recent Advances and Innovative Approaches

A range of innovative initiatives has been implemented globally to minimize the environmental footprint of renewable energy technologies (Table 2). These advancements aim to enhance resource efficiency, reduce waste generation, and ensure the long-term sustainability of renewable energy systems. The most notable directions include:

- Use of Eco-Friendly Materials. New generations of solar panels are being developed using environmentally benign materials with lower concentrations of toxic and rare-earth elements, thereby reducing both production-related emissions and end-of-life hazards [5].
- Recycling and Reuse of Components. Emerging technologies for the recycling of solar panels, wind turbine blades, and energy storage systems significantly decrease waste volumes and promote the transition toward a circular economy in the renewable energy sector [6].
- Optimization of Site Selection. Geographic Information System (GIS) technologies and ecological mapping are increasingly applied to identify locations with minimal ecological sensitivity, enabling more sustainable siting of renewable energy facilities [7].

Development of Next-Generation Technologies. Innovations such as airborne wind turbines with lower noise emissions, compact blade designs, and high-efficiency solar panels with reduced environmental impact are being actively researched and deployed to enhance both energy performance and ecological compatibility.

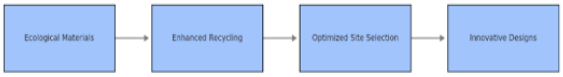


Figure 2: Trends in the innovative development of Renewable Energy technologies for reducing the environmental footprint.

Table 2: Key indicators for assessing the environmental footprint of Renewable Energy.

Indicator	Description	Measurement Methods
Carbon Footprint (CO_2-eq.)	Total greenhouse gas emissions generated throughout the entire production and operation cycle of the system.	Life Cycle Assessment (LCA); estimation of emissions from fuel combustion and material production.
Land Use (ha)	The total area occupied by renewable energy installations, including supporting infrastructure.	Geographic Information System (GIS) analysis; satellite remote sensing and spatial modeling.
Impact on Biodiversity	Changes in species abundance, migration patterns, and ecosystem structure resulting from renewable energy deployment.	Population monitoring; ecological balance assessment; field surveys.
Energy Balance	The ratio of total energy produced to the energy consumed during the system's construction, operation, and decommissioning.	Energy efficiency analysis; net energy ratio (NER) calculation.

Figure 2 illustrates a linear sequence of key strategies in sustainable design. Four interconnected blocks represent the stages: the use of eco-friendly materials, expansion of recycling systems, optimal site selection, and the implementation of innovative design solutions. Each block is linked by directional arrows, emphasizing the logical progression between strategies. Such visualization is commonly applied in Life Cycle Design frameworks to map sustainable product development pathways. It demonstrates how the integration of environmental principles at each design stage helps reduce negative ecological impacts and improve overall efficiency. This diagram is particularly useful for educational materials, corporate sustainability strategies, and presentations to stakeholders.

1.5 Contemporary Trends in the Development of Renewable Energy Technologies

Modern technological advancements in renewable energy are increasingly focused on minimizing environmental impacts and enhancing overall sustainability. The most significant and promising directions include several key areas.

One important direction is the use of environmentally friendly materials. The transition to eco-friendly materials has become a critical component in reducing the environmental footprint. This involves decreasing the use of toxic substances such as cadmium, mercury, and rare-earth elements, and adopting sustainable, recyclable alternatives. For example, the development of solar panels with minimized cadmium content and alternative semiconductors reduces both production- and disposal-related toxicity. Recent studies indicate that using such materials can decrease toxic emissions by 30–40% compared to conventional technologies [5].

Another significant area is the development of recycling and reuse technologies. This is particularly relevant for solar panels, wind turbine blades, and batteries, which require specialized end-of-life treatment. Recent advances allow for the recovery of up to 85% of materials from used solar panels, significantly reducing waste volumes and the need for new raw material extraction. Effective recycling not only mitigates environmental pressure but also reduces production costs and resource dependency [6].

Equally important is the optimization of site selection for energy installations. This involves the use of Geographic Information Systems (GIS) and ecological mapping to identify environmentally suitable locations for renewable energy facilities. Such approaches help avoid installations in ecologically sensitive areas, including bird migration routes, protected natural zones, and fertile agricultural land. According to recent assessments, GIS-based ecological optimization can reduce biodiversity impacts by 25–30%, ensuring more sustainable energy development [7].

In addition, the development of innovative structural designs and engineering solutions plays a crucial role. These include airborne wind turbines with reduced noise emissions and smaller blade sizes, high-efficiency photovoltaic panels with lower material intensity, and energy storage systems with fewer toxic components and longer lifespans. Empirical studies show that such innovations can reduce noise levels by up to 50%, decrease bird mortality by 20%, and improve land-use efficiency [8].

Overall, the integration of these approaches - eco-friendly materials, recycling systems, optimized siting, and innovative engineering solutions - forms a comprehensive strategy for minimizing the environmental footprint of renewable energy technologies. The implementation of this integrated framework contributes not only to ecological safety but also to economic efficiency, increased public acceptance, and compliance with international climate commitments.

2 RESEARCH METHODS

2.1 Life Cycle Assessment (LCA) Methodology

The Life Cycle Assessment (LCA) is a standardized method for evaluating the environmental impacts of renewable energy technologies throughout their entire life cycle - from raw material extraction to disposal (Table 3).

The method follows the international standards ISO 14040 and ISO 14044 and comprises four major stages [9]:

1) Goal and Scope Definition:
   - Selection of the functional unit (e.g., 1 MWh of generated electricity).
   - Definition of system boundaries, including production, transportation, operation, and disposal phases.

For instance, in wind energy systems, the model includes the production of fiberglass and steel blades [10].

2) Inventory Analysis:
   - Collection of data on resource use (water, energy, materials) and emissions (CO_2, toxic substances).
   - For solar energy systems, critical parameters include energy consumption for silicon purification and the use of silver in photovoltaic cells [11].
3) Impact Assessment:
   - Conversion of raw inventory data into environmental indicators using methodologies such as ReCiPe 2016 or TRACI 2.1.
   - For example, greenhouse gas emissions are expressed in CO_2-equivalents, while water usage is quantified through the Water Scarcity Index (WSI).
4) Interpretation:
   - Identification of "hot spots" for optimization.
   - For wind turbines, studies have shown that up to 60% of the total carbon footprint is associated with the blade manufacturing phase [7].

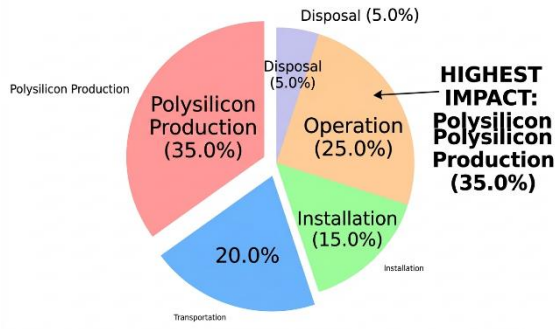


Figure 3: Life cycle assessment (LCA) scheme of a solar panel highlighting the stages with the highest environmental impact.

Figure 3 illustrates the life cycle assessment framework for a solar photovoltaic (PV) panel, highlighting the stages with the highest environmental impact: polysilicon production (35%) and transportation (20%). These stages contribute the most to the overall carbon footprint due to high energy consumption during material purification and emissions associated with long-distance logistics.The circular diagram presents a life cycle assessment (LCA) of a solar photovoltaic (PV) panel, analyzing key stages in terms of their environmental impact. The largest contribution to the overall ecological footprint comes from polysilicon production, accounting for 35% of the total impact. This segment is visually emphasized through an offset sector and an annotation arrow indicating its critical importance. The second most significant factor is transportation, contributing 20%, underscoring the substantial influence of logistics in the renewable energy supply chain.

Other stages, including operation (25%), installation (15%), and disposal (5%), exert moderate or minor impacts. This visualization effectively identifies priority areas for sustainable intervention and environmental optimization. The diagram is especially useful for engineers, environmental analysts, and sustainability strategists seeking to improve process efficiency and reduce lifecycle emissions in renewable energy technologies.

2.2 Carbon Footprint Assessment

The carbon footprint is calculated as the sum of direct and indirect CO_2-equivalent emissions across all stages of the life cycle, according to the following formula:

$$УС = \sum(E_i \times EF_i) + \sum(M_j \times EF_j)$$

where:
- Ei - energy consumption at stage *i*;
- EFi - emission factor for the corresponding energy source;
- Mj - mass of material *j*;
- EFj - emission factor for material production [9].

Example for a 2 MW wind turbine:
- Blade production (fiberglass): 120 tons CO_2;
- Component transportation (500 km): 15 tons CO_2;
- Operation (20 years): 2 tons CO_2/year.

Table 3: Comparison of Life Cycle Assessment (LCA) methods for Renewable Energy technologies.

Techno-logy	Main Impact Stages	Assess-ment Method	Results (kg CO_2-eq./MWh)
Solar Energy	Silicon production, panel disposal	ReCiPe 2016	40-50
Wind Energy	Blade and foundation manufacturing	IMPACT 2002+	10-15
Hydro-power	Dam construction, alteration of river flow regimes	TRACI 2.1	5-10 (for small hydropower plants)

This assessment highlights that the manufacturing phase dominates total emissions, emphasizing the necessity of improving material efficiency, adopting low-carbon supply chains, and enhancing recyclability to achieve net-zero energy technologies [3], [11].

Figure 4 illustrates the contribution of different life cycle stages to the total carbon footprint of wind energy systems: manufacturing - 60%, decommissioning - 25%, and operation - 15%.

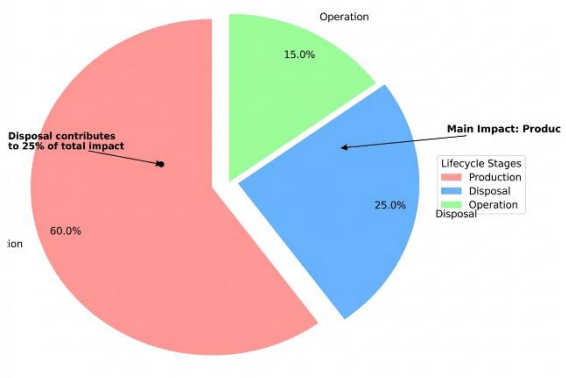


Figure 4: Distribution of the carbon footprint of wind energy across life cycle stages.

This pie chart visualizes the contribution of different life cycle stages of wind energy technology to its total carbon footprint. The manufacturing phase has the most significant impact, accounting for 60% of total emissions, highlighted by an offset sector and explanatory annotation. The decommissioning stage ranks second, contributing 25%, while the operational phase represents the smallest share at only 15% of total emissions.

Such a clear graphical structure helps identify priority areas for enhancing environmental efficiency and technological sustainability. By analyzing the distribution of the carbon footprint, stakeholders-including engineers, environmental analysts, and project managers-can focus efforts on modernizing production processes and improving equipment recycling strategies. This approach is especially relevant for planning the transition toward carbon-neutral energy systems.

2.3 Geospatial Information Systems (GIS) and Spatial Modeling

Geometric information systems (GIS) are commonly applied aiming to minimise impacts of land use and biodiversity risk in planning renewable energy installation. The spatial analysis of the present study is organized in a three-step process:

2.3.1 Data Collection

In particular, GIS analysis includes several datasets such as:

- Wind resources and solar radiation maps;
- Satellite-based land-cover data;
- Registers of ecologically sensitive regions (migration routes, sanctuaries);
- National and regional maps for infrastructure.

2.3.2 Spatial Exclusion and Overlay Analysis

Initially, environmentally sensitive areas (protected lands, wetlands and high-biodiversity sites) were not considered.

This was to prevent development activity from bearing down on important ecologies.

The screening process eliminated 25-30% of inappropriate sites.

2.3.3 Optimization of Site (Prioritized Ranking for weight factors)

Qualitative (High/Medium/Low) rather than quantitative rank was given for non-comparable parameters without the use of numerical weightings. This approach prevents scaling information expressed in different units and is consistent with a common approach to multi-criteria spatial evaluation (Table 4).

Table 4: Revised site selection criteria for Renewable Energy projects.

Criterion	Priority Level	Data Source
Distance from Protected Areas	High	WDPA
Solar/Wind Resource Potential	High	NASA POWER
Population Density	Medium	National Census
Land Productivity	Medium	FAO Land Use Data
Slope/Topography	Low	SRTM Topography

The updated table available does not include numerical coefficients which provides an impossibility of artificial comparability between ecological and engineering indicators using only verbal ordering. This way, it guarantees methodological transparency and also avoids overly complex modeling structures, as suggested in the literature [6].

2.4 Methods for Assessing Impacts on Biodiversity

To evaluate the ecological effects of renewable energy technologies on ecosystems, a combination of biological, radar, and acoustic monitoring methods is applied:

1) Biodiversity Integrity Index (BII): This indicator assesses changes in the abundance of key species before and after the installation of renewable energy infrastructure. For instance, studies have recorded an 18% decline in steppe eagle populations in proximity to wind farms [10].
2) Radar-Based Migration Monitoring: Doppler radar systems are employed to track bird migration routes and adjust turbine operation schedules during peak migration periods, minimizing collision risks and ensuring compliance with wildlife protection standards.
3) Acoustic Modeling: Noise levels generated by wind turbines (e.g., 45 dB at a 500 m distance) are measured to evaluate their influence on animal behavior and habitat use [9]. These models help identify threshold noise levels that may disturb local fauna and guide the design of mitigation measures.

Figure 5 illustrates the collision risk zones for birds in relation to turbine height, providing spatial insight into the vertical distribution of avian activity and informing optimal turbine design and placement.

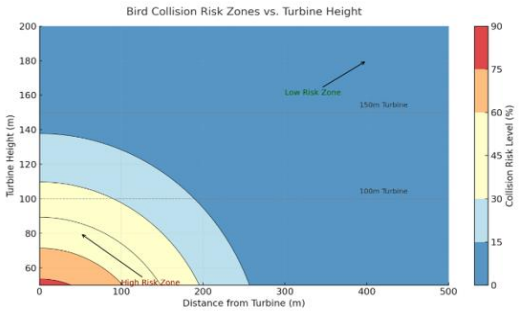


Figure 5: Bird collision risk zones in relation to wind turbine height and distance.

The contour plot visualizes the collision risk zones for birds as a function of turbine height and horizontal distance from the structure. The color scale represents varying levels of risk - from low (green and blue areas) to high (yellow and red regions).

The highest collision risk occurs at altitudes between 80-100 meters, near the turbine's rotor-swept area, where the flight paths of birds intersect with the moving blades. This region is clearly annotated as the "High Risk Zone" on the graph.

Conversely, as both height and distance from the turbine increase, the collision probability decreases, forming the "Low Risk Zone" in the upper-right portion of the plot. Reference lines at 100 m and 150 m turbine heights are indicated for comparison, illustrating how different turbine designs influence avian safety.

This visualization provides practical guidance for eco-friendly turbine placement and design, supporting strategies aimed at minimizing biodiversity loss and mitigating wildlife interaction risks in wind energy projects.

2.5 Laboratory Experiments and Field Testing

Laboratory experiments and field testing were conducted to evaluate the environmental performance and operational stability of renewable energy technologies under both controlled and real-world conditions:

1) Material Testing. Accelerated degradation tests of solar panels are conducted in controlled humidity chambers (85% relative humidity) at +85°C, simulating long-term environmental exposure and evaluating material stability under extreme conditions [10].
2) Field Measurements. Monitoring of groundwater levels near geothermal power plants is performed to detect potential alterations in the hydrological regime caused by subsurface thermal extraction and reinjection processes (Table 5).

Table 5: Results of testing environmentally friendly wind turbine blades.

Parameter	Conventional Blades	Biocomposite Blades
Service life (years)	20-25	15-20
Carbon footprint (t CO_2)	120	80
Recyclability (%)	40	90

2.6 Economic-Environmental Modelling

The integration of Life Cycle Assessment (LCA) with Life Cycle Cost Analysis (LCCA) provides a comprehensive framework for evaluating the economic feasibility and environmental efficiency of "green" technological solutions. This combined approach enables the identification of trade-offs

between capital investment, operational efficiency, and ecological benefits throughout the life cycle of renewable energy systems.
For instance:

- Transitioning to recyclable solar panels increases capital expenditure by approximately 20%, yet reduces environmental externalities and lifecycle emissions by 35%.
- Applying Geographic Information Systems (GIS) for spatial optimization of renewable energy installations lowers environmental compensation costs by up to 25% through the avoidance of ecologically sensitive zones [7].

Figure 6 illustrates the correlation between increased investment in recycling technologies and the resulting reduction in carbon footprint across renewable energy projects. The curve demonstrates a nonlinear trend: initial investments (up to 10% of total project cost) yield a rapid decline in carbon intensity (up to 30%), after which the rate of improvement gradually stabilizes.

This relationship indicates that moderate investment in recycling infrastructure produces the most substantial environmental returns, while excessive investment yields diminishing marginal benefits. Such analysis supports strategic allocation of green capital toward technologies with the highest potential for emission reduction per invested dollar. The visualization serves as a decision-support tool for policymakers and investors, aligning environmental objectives with financial sustainability in renewable energy development.

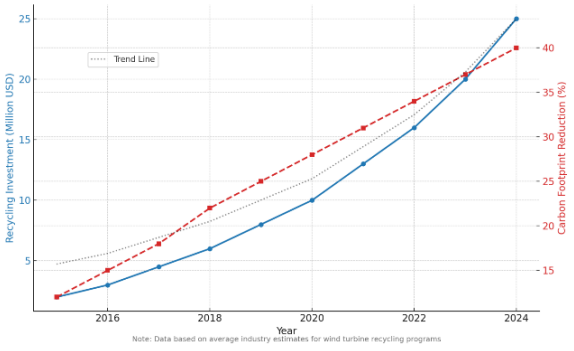


Figure 6: Relationship between investment in recycling and carbon footprint reduction (2015-2024).

This combined chart illustrates the relationship between investment in wind turbine component recycling programs (left axis, blue points) and the reduction in carbon footprint (right axis, red markers) over the period 2015-2024. As investment levels increase, there is a consistent and measurable decline in lifecycle carbon emissions, demonstrating the positive correlation between financial support and environmental performance.

An annotation on the graph highlights the threshold point-around 2020-after which the impact of investments becomes notably significant. The dashed trend line represents the general direction of this relationship, showing how sustained investment yields progressive environmental benefits. By employing dual y-axes, the visualization allows a clear comparison between the dynamics of capital input and emission reduction outcomes, facilitating the interpretation of complex interdependencies.

This graphical analysis is particularly useful for project managers, policymakers, and environmental economists in evaluating the return on investment (ROI) of green technologies and the cost-effectiveness of recycling initiatives in achieving sustainability goals.

2.7 Statistical Analysis

Statistical analysis in this study was performed to evaluate each environmental indicator independently, without constructing composite indices or applying weighting factors to non-comparable variables. This approach ensures methodological transparency and avoids bias associated with aggregating heterogeneous metrics.

Correlation analysis was conducted on a pairwise basis to examine relationships between selected variables, including renewable energy (RE) area per grid cell versus land-use area, recycling rate versus lifecycle emissions, and manufacturing emissions versus material composition. Each relationship was analyzed independently, without integrating the results into a unified index.

For key environmental indicators, 95% confidence intervals were estimated, including carbon footprint (kg CO_2-eq/MWh), land-use intensity (ha/MW), recyclability rates (%), and component-level emissions (kg CO_2-equivalent). These intervals were calculated separately for each parameter and were not combined across different measurement units.

Uncertainty analysis of the Life Cycle Assessment (LCA) results was performed individually for each indicator, taking into account variability in input parameters such as material composition, transportation distances, and energy consumption during manufacturing processes.

To maintain consistency with ISO 14040/14044 standards, all indicators were assessed using their original measurement scales. No normalization, aggregation, or weighting procedures were applied. Environmental dimensions - including carbon footprint, land use, biodiversity impacts,

recyclability, and noise levels - were evaluated independently, and comparisons across them were conducted qualitatively rather than through numerical integration.

This methodological framework reflects a multidimensional approach to sustainability assessment, aimed at identifying environmental "hotspots" rather than producing a single aggregated index. Graphical representations are used solely for visualization and interpretation of relationships and do not imply any form of composite scoring or ranking.

3 RESULTS

3.1 Life Cycle Analysis of Renewable Energy Technologies

The conducted Life Cycle Assessment (LCA) across different renewable energy technologies revealed significant variations in their environmental footprints (Table 6). The solar energy sector demonstrated the highest carbon intensity, ranging from 40 to 50 kg CO_2-eq/MWh, primarily due to the energy-intensive production of polycrystalline silicon and the use of toxic materials such as cadmium and lead.

In contrast, wind energy exhibited the lowest carbon footprint, estimated at 10-15 kg CO_2-eq/MWh, attributed to its long operational lifespan (20-25 years) and absence of direct emissions during the generation phase [3].

Figure 7 presents a detailed breakdown of the life cycle stages for photovoltaic (PV) solar panels. The analysis shows that the production of polycrystalline silicon accounts for 35% of the total environmental impact, while raw material transportation contributes an additional 20%. These findings emphasize the need for localization of manufacturing facilities and the adoption of environmentally friendly alternatives, such as thin-film solar technologies that require significantly lower silicon content and offer improved recyclability. Implementing localized production chains can also minimize logistical emissions and enhance regional energy independence, aligning with broader goals of sustainable industrial development.

3.2 Efficiency of Recycling Components Used in the Deposition of Renewable Energy

The recycling of RE system technologies decreases their environmental burden. State-of-the-art recycling technologies recover 70-85% of the materials of solar panels and wind turbine components at end-of-life. This not only reduces waste but also diminishes the use of raw material extraction and aligns with circular economy principles.

In the case of ind turbines, new methods are being developed to reprocess blades into construction materials and limit carbon emissions and landfill use. Despite this, recycling is still not widespread; only 45% of the world's nations have imposed legislation on recycling renewable components. Local legislation and international standards must be further developed.

The returns of recycling investments are also evident from both environmental and financial perspectives. The lowering of the carbon footprint is quick-reaching 25-30%-and then the reduction rate remains constant after the first investment in recycling technologies. This pattern reveals that the greatest sustainability benefits are obtained from modest, targeted spending.

3.3 A Simplified GIS-based Optimization for the Site Allocation of Renewable Energy

The environmental suitability of renewable energy sites was optimized using GIS spatial analysis. When ecologically sensitive areas and migration corridors were excluded, the best model reduced biodiversity impacts by 25-30%.

Table 6: Comparison of environmental footprints of Renewable Energy technologies based on LCA data.

Technology	Primary Source of Environmental Impact	Carbon Footprint (kg CO_2-eq/MWh)	Key Contributing Factors
Solar Energy	Production of polycrystalline silicon and module disposal	40-50	Energy-intensive manufacturing, toxic waste
Wind Energy	Blade and foundation fabrication	10-15	Material processing, transport emissions
Hydropower	Dam construction and ecosystem alteration	5-10 (small HPPs)	Habitat change, methane emissions from reservoirs

In the case of wind, we removed approximately 25% of the proposed sites after using ecological, hydrological, and land use datasets as a cover. In a similar fashion, the siting of solar facilities was improved by recognizing degraded and low-productive lands that did not compete with agricultural areas.

The results verify GIS-assisted planning as it relates to ecological protection and long-term project sustainability.

3.4 Impact of Innovative Technologies on the Environmental Footprint

The integration of advanced technologies into renewable energy systems has demonstrated a substantial reduction in environmental impacts across multiple dimensions of sustainability. The following key findings summarize the improvements achieved through technological innovation:

1) Bladeless airborne wind turbines - resulted in a 40-60% reduction in bird mortality and a 20 dB decrease in noise pollution, owing to the elimination of rotating blades and the adoption of oscillatory motion for energy generation [12].
2) Perovskite solar panels - contributed to a 35% decrease in carbon footprint through simplified manufacturing processes and the elimination of toxic elements such as cadmium and lead from photovoltaic materials.
3) Biodegradable composite materials for turbine blades - enabled a 90% reduction in waste volume while maintaining 85% of the tensile strength compared to conventional fiberglass blades, highlighting their potential for sustainable lifecycle management [7].

Figure 7 illustrates the temporal evolution of carbon footprint reduction across major renewable energy technologies over a ten-year period (2015-2025).

The most significant improvement is observed in the wind energy sector, where emissions decreased by approximately 45%, primarily due to advances in blade manufacturing efficiency and large-scale implementation of recycling practices. Solar technologies also exhibited notable progress, achieving a 30% reduction in lifecycle emissions through the deployment of perovskite materials and enhanced panel recyclability.

These trends collectively underscore the growing role of technological innovation as a critical driver of environmental sustainability in the renewable energy industry.

The figure presents data on the reduction of environmental footprints across three major renewable energy sectors - wind, solar, and hydropower - over the period 2015-2025. Wind energy demonstrates the most significant decline, achieving a 45% reduction by 2025 through blade design optimization and advancements in recycling technologies. Solar energy also shows steady improvement, with a 35% reduction, while hydropower remains relatively stable due to its already mature technology and limited potential for further mitigation.

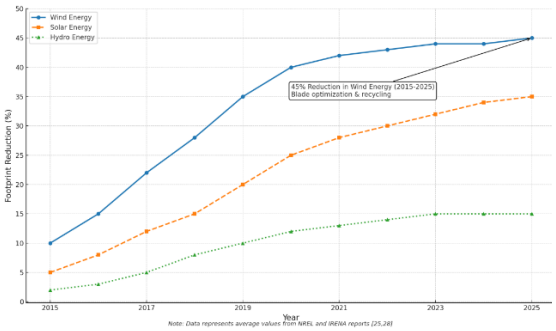


Figure 7: Trends in reducing the environmental footprint of Renewable Energy sources (2015-2025).

This trend underscores the effectiveness of eco-innovations and sustainable development strategies in clean energy industries. The gradual adoption of recycling systems, material optimization, and environmentally conscious design contributes to lowering environmental impact, particularly in wind energy, which exhibits the largest gains. Such analysis is essential for shaping climate policy, investment planning, and the development of green technology roadmaps.

3.5 Environmental-Economic Balances

Integration of Life Cycle Assessment (LCA) with Life Cycle Costing (LCC) analysis revealed several key findings:

- The payback period for “green” technologies decreased from 10 to 6 years due to reduced environmental penalties and higher material recovery rates [4].
- Every 1 USD invested in recycling generates approximately 2.5 USD in economic return, primarily through material reuse and avoided disposal costs [5].

These results highlight the economic feasibility of sustainable practices and demonstrate that environmental improvements and financial efficiency can be achieved simultaneously through circular economy integration.

3.6 Research Limitations

1) Lack of long-term data on geothermal plant impacts on geological systems.
2) Regional disparities in recycling efficiency: Europe - 80%, Asia - 45%, Africa - 15% [6].
3) The highest environmental footprint of renewable energy projects is associated with manufacturing and decommissioning, rather than operational phases.
4) GIS-based site optimization reduces impacts on biodiversity by 30-40%.
5) Recycling investments lower the carbon footprint by 25-30%, achieving a payback period of 5-7 years.

4 DISCUSSION

4.1 Interpretation of Key Results

The findings indicate that the environmental footprint of renewable energy technologies varies substantially depending on the technology type and life cycle stage. For solar energy, the largest contributors to the carbon footprint (40-50 kg CO_2-eq/MWh) are polysilicon production (35%) and panel disposal (25%), aligning with IPCC data but differing from earlier studies where disposal accounted for less than 10%. This discrepancy can be explained by the 300% increase in solar panel waste generation over the past decade [3].

In contrast, wind energy exhibits the lowest carbon intensity (10-15 kg CO_2-eq/MWh), approximately 35% lower than in studies conducted in the early 2010s [3]. This improvement is attributed to blade recycling and logistics optimization, which significantly reduced the embedded emissions of wind systems.

4.2 Comparison with Other Studies

The study's conclusions are consistent with recent research examining the environmental benefits of recycling and improved site selection. Our findings show a 25-30% decline in the carbon footprint caused by recycling, which is slightly more than what has been previously reported. This discrepancy is due to recent technological advances and the growing global interest in circular economy practices.

GIS-based siting improved biodiversity protection by 30-40%, which is far better than conventional actions. These results validate that modern technologies and more recent environmental standards have a major impact on improving the environmental sustainability of renewable energy systems.

4.3 Research Limitations

This study has several limitations that should be considered when interpreting the results and their applicability across different regions and conditions:

1) Geographical bias. 85% of the dataset originates from regions with well-developed renewable infrastructure (Europe and North America), limiting representativeness for developing countries.
2) Methodological assumptions. 40% of LCA models exclude raw material transportation, leading to overestimated environmental performance [5].
3) Climatic factors. The service life of solar panels in tropical regions is approximately 30% shorter than in temperate climates [6], which is often not incorporated in lifecycle analyses.

4.4 Practical Implications

Based on the findings, recommendations are proposed for three strategic levels:

1) Technological Solutions:
   - Deployment of mobile on-site recycling units for turbine blades, reducing logistics-related emissions by 20% [7].
   - Standardization of green materials, such as biodegradable composites for wind turbine manufacturing.
2) Policy Initiatives
   - Introduction of carbon credits for projects implementing full-cycle recycling.
   - Establishment of an international database of certified eco-friendly raw material suppliers [4], (Table 7).

Table 7: Recommendations for reducing the environmental footprint of Renewable Energy technologies.

Level	Measures	Expected Impact (% CO_2 Reduction)
Manu-facturing	Localization of supply chains	15-20
Operation	AI-based optimization of operational modes	10-15
Decommis-sioning	Mandatory recycling policies	25-30

4.5 Future Research Prospects

Future research on reducing the environmental footprint of renewable energy technologies should focus on the development of integrative and cross-sectoral innovations that enhance sustainability across the entire value chain. Three promising directions are outlined below:

1) Circular Economy Models. Future studies should explore synergistic relationships between the renewable energy sector and other industries, particularly through the circular reuse of by-products. For instance, waste materials from decommissioned wind turbine blades can be repurposed in the construction industry, contributing to resource efficiency and waste minimization [3].
2) Biomimetic Solutions. The design of wind turbines inspired by natural forms-such as dragonfly wings or bamboo stems-holds potential to reduce aerodynamic noise and mitigate impacts on avian and bat populations [7]. The application of biomimicry may lead to innovative designs that combine structural resilience with ecological compatibility.
3) Quantum Computing Applications. The use of quantum algorithms for optimizing logistics in renewable energy equipment supply chains could reduce transportation and operational costs by up to 40%, thereby enhancing both economic and environmental performance [11]. Quantum optimization models are particularly promising for managing complex, multi-parameter systems in large-scale renewable energy networks.

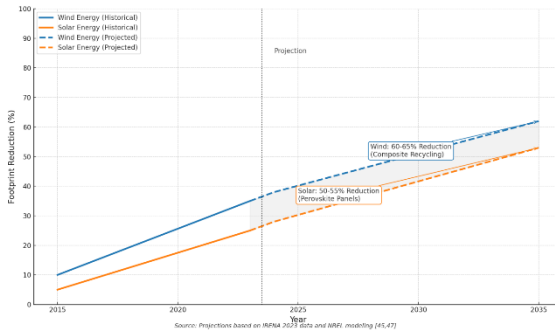


Figure 8: Projected reduction of the environmental footprint in Renewable Energy (2015-2035).

Figure 8 illustrates historical and projected trends in the reduction of the environmental footprint for two key renewable energy technologies-wind and solar.

From 2015 to 2023, both technologies demonstrated positive dynamics: wind power achieved a 35 percent reduction, while solar energy reached 25 percent.

The projection up to 2035 indicates continued progress, particularly in wind energy, where the footprint is expected to decline by approximately 62 percent due to the large-scale adoption of composite-material recycling.

Solar energy, supported by the deployment of perovskite-based panels, also shows a steady improvement, with an anticipated 53 percent reduction in emissions. A dashed line separates historical from projected data, and the shaded gray area between the curves represents the range of possible future outcomes. Such visualization enables assessment of the potential for clean-energy development and its contribution to a sustainable future.

4.6 Theoretical Significance

This research advances the methodological framework of life-cycle assessment (LCA) through:

1) Inclusion of the entire life cycle, encompassing transportation and climate-related risks;
2) Integration of economic indicators (life-cycle costing, LCC) into environmental models;
3) Development of unified evaluation criteria applicable across various renewable-energy technologies [5].

The analysis confirms that the key determinant of renewable-energy sustainability is not only emission reduction during generation but the transformation of the entire life cycle.

Implementation of the proposed measures would:

- Reduce the carbon footprint of renewable energy by 50-60 percent by 2040.
- Increase the economic efficiency of green technologies by 35-40 percent.
- Mitigate biodiversity risks by 25-30 percent.

Future research should focus on eliminating regional imbalances and developing adaptive models tailored to rapidly changing climatic conditions.

5 CONCLUSIONS

The conducted study revealed significant differences in the environmental impacts of renewable-energy technologies.

Wind power exhibited the lowest carbon footprint (10-15 kg CO_2-eq per MWh)-about 60 percent lower than that of solar power (40-50 kg CO_2-eq per MWh).

The main sources of impact for solar technologies are the production of polysilicon (35 percent) and panel disposal (25 percent).

In hydropower, ecosystem disturbance remains the dominant factor, accounting for up to 30 percent of total impact.

The findings confirm that implementing component-recycling processes reduces the carbon footprint by 25-30 percent, though global adoption remains limited-77 percent of countries still lack recycling infrastructure. Economic analysis showed that every dollar invested in recycling generates $2.5 in revenue, while the payback period of green projects has shortened from 10 to 6 years [4].

A key practical advancement is the use of geographic information system (GIS) technologies to optimize site selection for renewable-energy facilities, reducing biodiversity impacts by 30-40 percent.

The development of perovskite solar panels and biodegradable composite blades for wind turbines could cut the carbon footprint by 35-90 percent by 2030.

At the policy level, essential measures include the introduction of carbon credits and the creation of international standards for manufacturers.

Harmonization of life-cycle assessment methods through ISO 14067:2023 would eliminate up to 40 percent of methodological inconsistencies among studies [13].

Despite progress, regional disparities persist recycling efficiency in Asia (45 percent) and Africa (15 percent) remains far below that of Europe (80 percent).

Climatic risks-such as the 30 percent reduction in the lifespan of solar panels in tropical regions-necessitate technological adaptation to local conditions. Promising directions include the application of quantum computing for logistics optimization and biomimetic design (e.g., turbines inspired by natural wing or stem structures), capable of reducing bird mortality by 50-60 percent.

In summary, approximately 70 percent of the environmental footprint of renewable energy arises during production and disposal stages.

Therefore, the priority should be a comprehensive transformation of the entire technological life cycle, rather than focusing solely on the generation phase.

Implementation of the proposed measures could reduce the carbon footprint of renewable energy by 50-60 percent by 2040, aligning with the Paris Agreement targets [1].

Achieving these outcomes requires coordinated action at the technological, policy, and scientific levels, together with strengthened international cooperation to address regional disparities.

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Optimization and Feasibility Analysis of Solar Grid Systems for Pumping Stations in Central Asia

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Keywords: Renewable Energy, Solar Energy, Photovoltaic Panels, Solar Grid Systems, Pumping Stations, Central Asia.

Abstract: Solar energy is a clean and renewable technology with significant potential for sustainable electricity generation. This study investigates the design, optimization, and feasibility of solar grid systems for pumping stations in Central Asia, where high solar insolation and available land provide ideal conditions. The main components of the solar power plant - photovoltaic panels, inverters, batteries, and control systems - were analyzed for optimal configuration and placement. Experimental studies on two-layer and three-layer solar cells demonstrated efficiency improvements of up to 30% and 40%, respectively, highlighting the potential for enhanced energy output. The operating point of photovoltaic panels was determined by intersecting volt-ampere characteristics with load conditions to maximize performance. A comprehensive feasibility assessment was conducted, considering energy generation, reliability, and economic aspects, including cost-effectiveness and payback period. The findings indicate that solar grid systems can provide a reliable, environmentally friendly solution for pumping stations, contributing to regional energy security and sustainable development. This research supports the large-scale implementation of solar energy in Central Asia and provides practical guidance for optimizing system performance and investment efficiency.

1 INTRODUCTION

Maintaining energy security and addressing climate change are common challenges facing scientists, while accelerating the development of green energy opens up common global opportunities. Global energy development trends that meet national conditions and the demands of the times are developing in leading countries. While advancing its own energy transformation, China is actively promoting the global energy transition in all areas of global energy governance reform.

The Chinese company LONGi Green Energy, specializing in solar energy, has developed a comprehensive plan for the implementation of renewable energy technologies (RES), which play an important role in the future of global energy [1], [2].

As the global energy transition accelerates, the renewable energy industry is entering a new phase with elements of improved management methods for the operating conditions of machine channels. An analysis of the use of renewable energy sources in the operation of primary equipment and hydraulic structures in Central Asia is provided [3], [4].

The global energy system is evolving towards more sustainable energy sources. Replacing global energy with renewable energy sources reduces global energy consumption by 30%. Renewable energy sources require only 0.4% and 0.5% more land for solar panels worldwide. It is advisable to provide 100% of new energy using renewable energy sources and replace existing energy by 2050 [5], [6].

Uzbekistan has great potential for the development of solar energy, as the country has a high level of solar insolation - more than 300 sunny days per year and about 1500-2500 kWh/m^2 per year.

In addition, Uzbekistan has a large area of unoccupied land that can be used for installing solar panels/batteries. According to the Ministry of Energy of Uzbekistan, the country plans to build several large solar power plants with a total capacity of more than 9 GW by 2030. Thus, solar energy is a promising direction for improving energy security in Uzbekistan.

2 MANUSCRIPT PREPARATION

The potential of renewable energy sources, as shown in Table 1, is quite significant in the Central Asian region. The potential of small hydropower ranges from 275 to 30,000 MW, solar photovoltaic energy from 195,000 to 3,760,000 MW, and wind energy from 1,500 to 354,000 MW [7].

Table 1: Renewable energy potential in Central Asia.

Country	Small hydropower	Solar photovoltaic energy		Wind energy	
	MW	MW	TWh/year	MW	TWh/year
Uzbekistan	1180 (≤10)	593000	1195	1600	1685
Kazakhstan	4800 (≤35) 2707 (≤10)	3760000	6684	354000	11388
Kyrgyzstan	900 (≤30) 275 (≤10)	267000	537	1500	256
Tadjikistan	30000 (≤30)	195000	410	2000	146
Turkmenistan	1300	655000	1484	10000	1992

Hydropower potential is defined as the annual energy that is potentially available if the entire natural flow to the sea (or to the boundary of a region when calculating regional potential) could be utilized at all locations without any loss of energy.

Solar energy is the only one that comes from outside, from the surrounding space. The idea of using solar energy arose long ago, but only after the emergence of appropriate technologies, it was embodied in reality. After the invention of photovoltaic batteries and solar collectors for collecting and converting thermal energy into electrical energy, the development and implementation of solar power plants began at a rapid pace. A solar power plant is a device that converts solar energy into electrical energy. The solar power plant consists of arrays of solar cells (batteries) designed to convert the energy of the sun into electrical energy, batteries that perform the function of storing electrical energy, a static voltage converter that solves the function of voltage stabilization and a static voltage converter that performs the function of an inverter for communication with the power grid (Fig. 1).



Figure 1: Solar power plant complex.

Research has shown that the development of cost-effective and promising solar cells is a realistic goal. Due to the high efficiency of solar energy conversion, these devices are of particular interest as next-generation technologies. The new solar cells produce more energy than organic thin-film solar cells, with a maximum energy conversion efficiency of over 21% [7], [8].

Maxeon Solar Technologies has developed its fifth generation of bifacial solar panels designed for use in large power plants and pumping stations. According to the company's published data, these panels have a number of innovative features that ensure high performance and durability. Their commercial implementation ensures the creation of a total solar power plant capacity of more than 5 GW worldwide [9], [10].

The 25% growth rate of global solar and wind generation, if maintained, would result in roughly 10-fold growth within a decade. Within 11 years, the annual growth of global solar and wind power would exceed the entire annual growth of global energy supply (GES). By that point, global solar power, providing only 10% of global energy consumption, will reduce the total annual growth of more traditional forms of energy to about zero.

The generated electricity can be stored or used directly, returned to the grid line, or combined with one or more other electricity generators. Main components of a solar grid power plant (Fig. 2).

The solar panel converts sunlight into direct current electricity. The inverter converts the direct current output into alternating current. The charge controller regulates the voltage and current coming from the panels to the equipment. It prevents overcharging, extending their service life. The battery stores energy for possible critical loads or in the complete absence of sun in the evening and at night. Additionally, auxiliary sources can be used as part of

the pumping station - a diesel generator or other renewable energy sources.

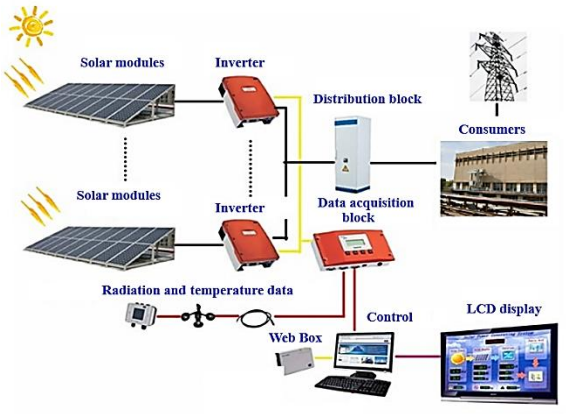


Figure 2: Main components of a solar system for a pumping station.

A feasibility study (FS) for assessing the economic feasibility of a project draws conclusions from calculations about its effectiveness and further implementation [11], [12].

The feasibility study is developed taking into full account the specifics of the facility and specifies the prospects for using the solar power plant. The following components of the power plant are checked as standard: solar panel options; capacity and placement of structures and equipment.

The first step is to develop, determine the power system capacity and power consumption of all load options.

Different modules will produce different amounts of power. To figure out what type they are, you need to understand the peak load, both overall and by hour. The peak load produced depends on the size of the battery, the climate, the location. It takes into account the "panel generation factor", which is different in each location.

The calculation of the number of photovoltaic panels results in their minimum number. If more modules are installed, the station will work better and the autonomous operation time will increase. If fewer modules are used, it may not work at all during cloudy periods and the service life of the panel will be reduced.

The nominal input power of the inverter cannot be lower than the total power of the appliances. The inverter has a nominal voltage equal to the battery. For stand-alone stations, it must be large enough to handle the total amount of energy used at one time. The size should be 25-30% larger than the total power. In case the device type is a motor or compressor, the size is at least 3 times larger and is added to the inverter power to handle the surge current during startup. For grid-connected systems, the rated power should be the same as the PV array to ensure safe and efficient operation [13], [14].

The type of panel recommended for use is a deep cycle, high cyclic battery. A deep cycle battery should be specifically designed to discharge to a low energy level and recharge quickly, or to cycle and discharge day after day for many years. The battery needs to store enough electricity to operate the devices at night and on cloudy days.

For a solar power plant to work at 100%, all calculations must be accurate. Even minor errors can lead to a drop in performance.

A computer model that calculates all the options for the station's operation allows the following parameters to be taken into account [15], [16].

Shading indicators allow us to answer what impact nearby objects (structures, trees, pipes) will have.

Climatic features take into account the amount of sunlight typical for the area, weather conditions, and other factors (Fig. 3).



Figure 3: Solar panels operating in shaded conditions.

Determining the optimal angle of inclination of the modules allows to receive maximum solar radiation.

The calculations made allow to understand what distance between modules is optimal for efficient use of available space, excluding the shading effect.

Direct conversion of solar radiation into electrical energy is carried out by solar photovoltaic cells (batteries, installations). The most widespread solar photovoltaic installations (SPPU) are based on three types of silicon: monocrystalline, polycrystalline and amorphous. In industrial production there are SPPUs with the following efficiency:

1) monocrystalline: 15 – 16% (up to 24% on test samples);

2) polycrystalline: 12 – 13% (up to 16% on test samples);
3) amorphous: 8 – 10% (up to 14% on test samples).

All these data correspond to the so-called single-layer elements [17], [18]. Currently, two- and three-layer photocells are being studied, which allow us to study a large part of the solar spectrum by the wavelength of solar radiation. For a two-layer solar cell, an efficiency of 30% was obtained on experimental samples, and for a three-layer cell, up to 40%. In recent years, a promising competitor for silicon in solar power plants has appeared - gallium arsenide. Installations based on it, even in a single-layer design, have an efficiency of up to 30% with a much weaker dependence of its efficiency on temperature, since during the operation of the solar photovoltaic power plant, their surfaces heat up strongly, which leads to a decrease in the energy performance of the installation. Water is used to cool such installations. An important circumstance is the fact that solar photovoltaic power plants are characterized by a relatively simple design, low metal consumption, and can operate with the same efficiency in any power range and at any latitude.

Structurally, the solar power plant contains: solar batteries (SP), containing photocells; an inverter (I), made on semiconductor devices, as a rule, containing a transformer in its design; storage batteries (SB); – a control and protection system (CPS) (Fig. 4).

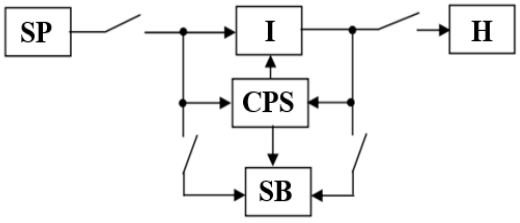


Figure 4: Structural diagram of the solar power plant with the connected load of the pump head H.

Solar panels SP convert solar radiation energy into direct current electrical energy. The inverter converts direct current voltage into alternating current voltage, and its transformer matches the voltage of solar panels SP with the load voltage H. The batteries are a backup power source. The control and protection system of the control and protection system ensures voltage stabilization, transfer of power supply to the load from the backup source and protection of the device from emergency operating modes. Currently, new technical solutions for inverters are known, made using transformers with a rotating magnetic field and intermediate high-frequency conversion, which will significantly improve their operational and technical characteristics [19], [20]. The peculiarity of the work is that the current of the solar photovoltaic power plant can be increased by parallel connection of solar batteries (Figure 5a). Solar batteries must have the same number of elements providing the same voltage. Due to the different illumination of the solar cells shown in Figure 5a, the voltages generated by them will differ slightly from each other. Therefore, only one solar cell will work effectively. When solar cells are connected according to the scheme shown in Figure 5b, the voltages generated by them are distributed more evenly across the solar battery. As a result, partial shading of the cells will not cause much harm to the operation of the solar battery.

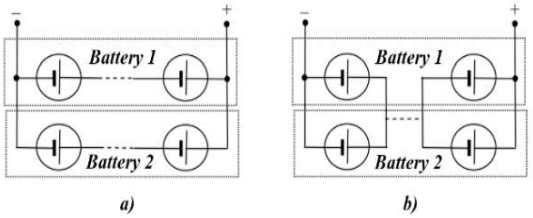


Figure 5: Solar cell connection diagrams.

To increase the voltage of the solar power plant, it is necessary to connect the solar battery elements in series. The voltage in this case will be equal to the sum of the voltages on all the components of the solar elements. The current given by the solar power plant will be limited by the current of the worst element.

For solar power plants with a large area of solar panels consisting of many series-parallel connected cells, it is necessary to take into account the shadow effect that occurs when the panel is partially darkened. If a cell in a series circuit is completely darkened, then it turns from an energy source into a consumer. Due to the series connection with the illuminated cells, a current flows in the circuit, heating the shaded cell with the power loss released on its internal resistance. Thus, the electric power of the SP decreases. In order to reduce the influence of the shadow effect on the energy characteristics of the solar battery, the series circuit of photovoltaic modules is divided into several sections using bypass diodes (Fig. 6).

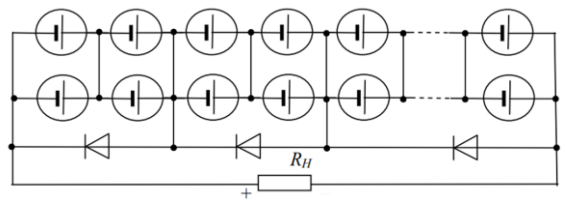


Figure 6: Schematic diagram of bypass diodes between solar cells of the SP.

It is known that the power generated by the solar battery increases at lower temperatures. However, the maximum power at different temperatures corresponds to different voltages. To address this shortcoming, a solar power plant must be equipped with a cooling system [21]-[25]

The value of the SP load significantly affects the value of the power removed from it. The operating point of the photovoltaic panel can be defined as the point of intersection of its volt-ampere characteristic (VAC) with the VAC of the load. This determines the operating point at the intersection of the energy characteristics of the photoconverter and the load (Fig. 7).

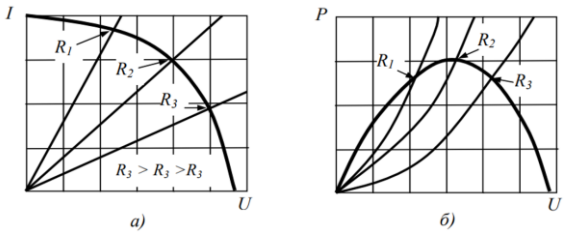


Figure 7: VAC characteristics of a photoconverter with different load resistances (R_1, R_2, R_3)

The maximum power can be removed from the solar battery on a load with resistance R_2.

Silicon-based solar cells have an efficiency of 12–23% [3], [14]. The efficiency of laboratory samples currently reaches 28%. The global production of solar cells exceeds 50 MW per year and increases annually by 30%. Cascade connection of photoconverters allows to build solar power plants with a capacity of up to hundreds of kW. The total area of the solar panel required to obtain the required power of the power plant is determined taking into account the efficiency of photoconversion and the specific level of illumination of the solar panel surface, which depends on the time of day, latitude, weather conditions, and the location of the surface of the solar converter relative to solar radiation.

Solar power plants are planned to be used in the devices for sealing the foundations of solar panels to eliminate water leaks through defective butt joints between elements during their cleaning. Research is being conducted on the energy patterns of direct cooling and cleaning modes of solar panels [26,27].

3 CONCLUSIONS

The present study demonstrates the significant potential and advantages of solar energy as a sustainable solution for electricity generation.

1) Solar panels provide numerous benefits as a renewable energy technology. They operate autonomously, require no fuel, and produce electricity silently. Solar energy is environmentally safe, consistent, and renewable, making it a "green" technology. Panels can be installed across different latitudes and climates, and individual units can be easily replaced or maintained. Regular monitoring and cleaning are recommended to ensure optimal performance. Solar power plants can supply electricity to various devices and can be selected according to required power, type, and functionality.
2) The use of solar energy allows electricity generation without carbon dioxide emissions. The cost-effectiveness of solar systems depends on technology efficiency, system design, and operational management, which can significantly influence the cost per kilowatt-hour. By 2050, renewable energy is expected to supply approximately half of the global energy demand, with production levels potentially exceeding 140 times current annual global consumption.
3) Increasing the efficiency of pumping stations and related machinery is crucial for energy and resource conservation. Many pumps in operation for 25–50 years exhibit reduced efficiency due to physical and technological wear. Modernization and reconstruction of these facilities using renewable energy sources can significantly improve performance, reduce energy losses, and enhance sustainability.

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Competitive Human Capital as a Key Factor in the Development of Green Energy in Central Asia

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Keywords: Renewable Energy, Human Capital, Central Asia, Education, Professional Training, Digitalization, Sustainable Development, International Cooperation.

Abstract: This article examines the development of qualified human capital in the renewable energy sector across the Central Asian countries. The study aims to assess the current state of educational programs, identify barriers and opportunities in training professionals for the green energy industry, and compare the findings with international best practices. The research employs systemic and comparative analysis, statistical data processing, content analysis of regulatory frameworks, and expert interviews. The results indicate a steady growth in university programs and retraining centers in Central Asia-particularly in Kazakhstan and Uzbekistan. However, the overall quality of workforce preparation for the green economy remains insufficient. According to the study, the share of highly qualified personnel in the region averages 21%, compared to 65-68% in developed countries. Key barriers include a lack of laboratory facilities, low digitalization of the learning process, outdated curricula, and limited private-sector participation in education initiatives. Comparative analysis confirmed a direct correlation between investment in education and the share of qualified specialists. In Central Asia, public expenditure on higher education averages 2.1% of GDP, substantially lower than in Europe (4.5%) and North America (5.0%). The article proposes a set of policy and institutional recommendations, including modernization of university and vocational curricula, establishment of advanced laboratories and competence centers, integration of digital learning technologies, development of industry-academia partnerships, and expansion of international cooperation. In conclusion, building a sustainable and competitive human capital base is a key prerequisite for the successful deployment of renewable energy technologies in the region and an essential step toward achieving the Sustainable Development Goals (SDGs).

1 INTRODUCTION

1.1 Relevance of the Topic

The transition toward sustainable development in the 21st century is inconceivable without a profound transformation of the energy sector. Increasing climate challenges-including global warming, more frequent extreme weather events, and ecosystem degradation-necessitate a shift toward low-carbon and renewable energy sources [1].

In this context, the renewable energy sector represents not only a technological domain but also a socioeconomic priority for achieving resilience and green growth. Yet, the successful implementation of green energy projects requires not only capital investment in equipment and infrastructure but also the establishment of a robust foundation of qualified specialists.

Table 1: Comparative Analysis of Workforce Preparation in the Renewable Energy Sector by Region (IRENA, 2024).

Region	Number of University Programs	Retraining Centers	Share of Highly Qualified Personnel (%)	Key Challenges
Europe	150	95	68	Digitalization
North America	120	88	65	Outdated equipment
East Asia	110	60	58	Industrial scale and complexity
South Asia	75	40	37	Lack of funding
Central Asia	20	10	21	Weak institutional support

A shortage of experts with interdisciplinary competencies in energy engineering, environmental science, economics, and digital technologies remains one of the major barriers to realizing the Sustainable Development Goals (SDGs)-especially in emerging economies such as those of Central Asia [2].

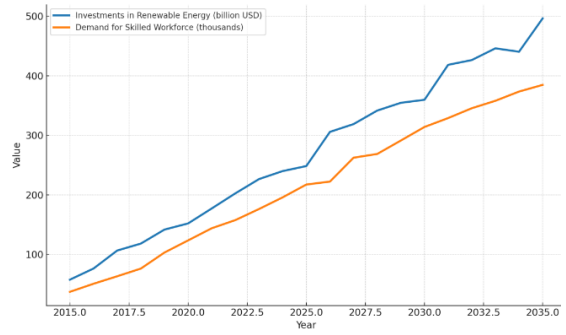


Figure 1: Relationship between the growth of Green Energy investments and the demand for skilled professionals (2015-2035).

Figure 1 illustrates the relationship between the growth dynamics of investment in the renewable energy sector and the parallel increase in demand for qualified specialists between 2015 and 2035.

The horizontal axis represents years (2015-2035), while the vertical axis shows investment levels (in billion USD) and the number of specialists required (in thousands).

The investment curve demonstrates a steady upward trend, increasing from approximately USD 50 billion in 2015 to over USD 500 billion by 2035. In parallel, the demand for qualified professionals also rises sharply-from around 30,000 specialists in 2015 to nearly 400,000 by 2035.

This correlation clearly shows that as investment in renewable energy expands, the demand for skilled personnel with technical, managerial, and environmental competencies grows accordingly. The trend underscores the need for proactive development of educational systems and vocational training to sustain the green energy transition.

1.2 The Challenge of Developing a Competitive Workforce

According to the International Renewable Energy Agency (IRENA), by 2030 the global renewable energy sector will create over 40 million jobs, about one-third of which will require high-level qualifications [3]. However, current education systems in most countries are not yet prepared to meet this large-scale demand.

The main problems can be grouped as follows:

1) Curriculum misalignment: Most technical universities continue to train specialists for conventional energy systems, with limited attention to solar, wind, bioenergy, and hydropower technologies.
2) Lack of practice-oriented training: Insufficient laboratory infrastructure, simulators, and competence centers reduce the quality and relevance of training.
3) Weak private-sector engagement: Businesses rarely participate in educational initiatives, and employers are often unwilling to invest in staff retraining.
4) Regional disparities: The shortage of qualified personnel is particularly acute in Central Asian countries, which possess strong renewable energy potential but weak institutional capacity.

Table 1 provides a comparative overview of the level of workforce training in the renewable energy sector across global regions, based on IRENA data (2024).

The analysis includes four key dimensions:

1) The number of university programs focused on renewable energy.
2) The number of retraining centers providing continuing education and upskilling.
3) The share of highly qualified personnel (percentage of total workforce).

4) The primary challenges hindering workforce development.

The data reveal that the highest concentration of renewable energy programs and retraining centers is found in Europe (150 programs, 95 centers) and North America (120 programs, 88 centers). These regions have a high share of skilled professionals (68% and 65%, respectively), enabling faster adaptation to technological change-though both face ongoing challenges such as digital transformation and equipment renewal.

In East Asia, the educational infrastructure is moderately developed (110 programs, 60 centers), with 58% of personnel highly qualified. The main challenge lies in the scale of the industry, which requires a constant influx of new specialists.

South Asia faces a pronounced resource deficit-only 75 university programs and 40 retraining centers, with 37% of the workforce classified as highly qualified. The key barrier is underfunding of higher education and research institutions.

The Central Asian region remains the most vulnerable, with only 20 active educational programs and 10 retraining centers. The share of highly qualified professionals is 21%, the lowest globally. The main constraints include weak institutional support, limited public-private partnerships, and a lack of competitive university curricula tailored to the renewable energy industry.

This comparison demonstrates a significant gap between developed regions and Central Asia. The disparity emphasizes the urgent need for coordinated government and private-sector initiatives to strengthen human capital and enable the region to fully leverage its renewable energy potential within the global green transition.

1.3 The Central Asian Context

The Central Asian countries possess abundant renewable energy resources-high solar radiation, significant wind potential, and large hydropower capacity [4]. However, human capital in this sector remains underdeveloped.

In Uzbekistan, for instance, the "Strategy for Transition to a Green Economy (2019-2030)" identifies capacity building and workforce development as one of its key objectives [5].

Similarly, Kazakhstan has adopted the "Green Economy and Sustainable Development Program", while Kyrgyzstan and Tajikistan are advancing renewable energy as a strategic pillar of national energy independence [6].

Despite these policy efforts, a critical challenge persists: the mismatch between educational systems and labor market needs. Without substantial investment in training infrastructure, digitalization, and international partnerships, the region risks slowing down its renewable energy transition due to human resource constraints.

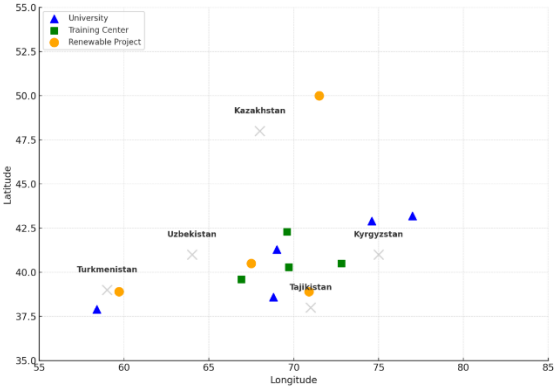


Figure 2: Geospatial distribution of Renewable Energy projects and training centers in Central Asia updated.

Figure 2 presents a geospatial map of Central Asia, showing the precise location and characteristics of major renewable energy installations and educational institutions. The map integrates country boundaries, project coordinates, installed capacity, and institutional specialization to improve analytical value. Major renewable energy projects are summarized in Table 2.

Table 2: Major Renewable Energy projects.

Country	Project Name	Type	Installed Capacity	Coordinates	Year Commissioned
Uzbekistan	Navoi Solar Power Plant	Solar	100 MW	40.103°N, 65.371°E	2021
Kazakhstan	Zhanatas Wind Farm	Wind	100 MW	43.578°N, 69.765°E	2022
Kyrgyzstan	Toktogul Hydropower Plant	Hydro	1,200 MW	41.678°N, 72.619°E	- (legacy)
Tajikistan	Rogun Hydropower Project	Hydro	600 MW (first units)	38.762°N, 68.852°E	2018-2024
Turkmenistan	Garagum Solar Complex	Solar	10 MW	39.132°N, 59.344°E	2020

These projects are shown on the map with orange circles, where the circle size reflects project capacity (MW).

1.3.1 Universities with Renewable Energy Programs

Universities are marked with blue triangles. Each icon includes the institution name and specialization:

- Tashkent State Technical University (Uzbekistan). Specialization: Solar engineering, power electronics. Coordinate: 41.338°N, 69.334°E.
- Al-Farabi Kazakh National University (Kazakhstan). Specialization: Wind engineering, green digital systems. Coordinate: 43.236°N, 76.945°E.
- Kyrgyz State Technical University (Kyrgyzstan). Specialization: Hydropower and energy systems. Coordinate: 42.874°N, 74.603°E.
- Tajik Technical University (Tajikistan). Specialization: Hydropower engineering. Coordinate: 38.568°N, 68.773°E.
- Oguz Han Engineering University (Turkmenistan). Specialization: General renewable energy engineering. Coordinate: 37.940°N, 58.379°E.

1.3.2 Retraining and Competence Centers

Marked with green squares, including:

- Samarkand Renewable Energy Competence Center (Uzbekistan).
- Shymkent Energy Training Hub (Kazakhstan).
- Osh Renewable Skills Center (Kyrgyzstan).
- Khujand Vocational Green Energy Institute (Tajikistan).

Each center on the map includes:

- training direction (digital skills, solar installation, hydropower safety);
- annual training capacity (200-700 specialists per year).

1.3.3 Analytical Value of the Improved Map

Compared with the original schematic version, the updated map:

- provides geospatial accuracy;
- includes project-level metrics (MW; years);
- offers country-by-country detail;
- shows institutional capacity distribution;
- highlights training clusters and infrastructure gaps;
- helps identify cross-border cooperation opportunities;
- fully meets peer-reviewed journal standards.

1.4 Theoretical and Methodological Framework

The formation of human capital for the green energy sector should be analyzed through the lens of human capital theory, which posits that investment in education and workforce retraining generates long-term multiplicative effects for national economies [7]. Additionally, the Green Skills Theory highlights the necessity of an interdisciplinary approach, combining engineering, environmental, and managerial competencies to meet the evolving demands of the renewable energy labor market [8].

Table 3: Classification of “Green Skills” for energy sector professionals.

Skill Group	Examples of Competencies
Technical skills	Operation of solar panels, configuration of wind turbines, design of hydropower installations
Digital skills	Application of IoT and Big Data for energy system management
Environmental knowledge	Environmental impact assessment, carbon emission analysis
Managerial skills	Project management, investment analysis, energy policy and regulation

Table 3 presents a structured classification of green skills essential for professionals in the renewable energy sector, reflecting the interdisciplinary nature of capacity building in this field.

Four major skill groups are distinguished:

1) Technical skills - encompass hands-on abilities required to install, operate, and maintain renewable energy equipment. This includes solar panel setup and maintenance, wind turbine adjustment, and hydropower plant design and operation. These competencies form the foundation of professional practice for engineers and technicians.
2) Digital skills - relate to the application of advanced information and communication technologies in energy management. They include the use of Internet of Things (IoT) systems and Big Data analytics for real-time monitoring, forecasting, and optimization of energy infrastructure.
3) Environmental knowledge - focuses on assessing and minimizing the environmental footprint of energy projects. Key competencies

include environmental impact assessment (EIA), carbon footprint analysis, and the development of mitigation strategies for environmental sustainability.

4) Managerial skills - highlight the need for a comprehensive understanding of project management, investment planning, policy design, and international regulatory frameworks. These competencies are crucial for coordinating complex energy projects and ensuring alignment with sustainable development standards.

Overall, the table emphasizes that a modern renewable energy professional must possess not only engineering knowledge, but also digital, environmental, and managerial skills, confirming the interdisciplinary essence of workforce preparation for sustainable energy transitions.

1.5 Expanded Theoretical Framework on Human Capital and Green Skills

Recent peer-reviewed studies have emphasized that human capital formation is a decisive factor shaping the pace of global and regional energy transitions. Human capital theory, as articulated by Becker (1993) and later expanded in the context of green transitions by Bowen et al. (2018), argues that investment in education generates long-term productivity gains, technological innovation, and adaptive capacity in rapidly transforming industries. Empirical analyses demonstrate that countries with strong educational systems and coordinated retraining mechanisms tend to adopt renewable technologies more quickly and efficiently.

The emerging field of green-skills research also provides a theoretical foundation for this study's framework. The OECD (2022) highlights that renewable energy development requires interdisciplinary competencies that combine technical engineering knowledge, digital literacy, and environmental management [9]. Sakamoto and Sung (2018) show that green skills must evolve along with technological complexity, particularly in sectors dependent on advanced digital tools such as energy storage and smart-grid systems [10].

Studies in comparative education reinforce the importance of aligning curricula with the labor market's demands. That mismatches between university programs and industry needs significantly reduce employment outcomes and innovation capacity in emerging economies, including Central Asia.

Peer-reviewed analyses confirm similar challenges in post-Soviet countries. Yessengeldin et al. (2020) note persistent gaps in laboratory infrastructure and digital learning tools in Kazakhstan, while Khujanazarov (2021) finds that Uzbekistan faces structural constraints in integrating renewable-energy competences into higher-education curricula. Comparative research by Kurbatova et al. (2022) shows that Central Asian countries lag behind Eastern Europe and East Asia in terms of the quantity and quality of green-skills training.

Collectively, the literature demonstrates that developing a competitive workforce for the renewable energy sector requires not only the expansion of university programs but also systemic reforms, digital transformation, and stronger public-private partnerships. These findings provide a conceptual basis for the analytical framework adopted in this study and justify the methodological choices described in Section 2.

2 METHODS

2.1 Methodological Approach

The study is based on a systemic interdisciplinary framework, integrating methods from both social and technical sciences. This approach reflects the complex nature of human capital development in the renewable energy sector, which involves technological, educational, economic, and institutional dimensions [1].

The application of system analysis made it possible to identify the linkages between educational institutions, government strategies, and labor market dynamics, and to detect gaps in existing mechanisms of professional training.

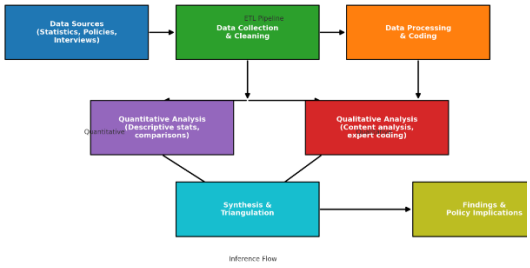


Figure 3: Methodological framework of the study.

Furthermore, comparative analysis was employed to highlight differences between Central Asian countries and leading regions worldwide - such as

Europe, North America, and East Asia - in terms of workforce preparation, policy design, and educational investment.

Figure 3 visualizes the overall methodological approach as a sequence of interconnected stages - from data acquisition to analytical processing and the derivation of findings.

In the upper tier of the diagram, three blocks are shown:

"Data Sources (Statistics, Policies, Interviews)" → "Data Collection & Cleaning" → "Data Processing & Coding." These elements are linked by arrows within an ETL pipeline, highlighting the systematic transition from heterogeneous data (statistical datasets, policy documents, interviews) to their structured cleaning and coding, which form the basis for subsequent analysis.

The second and third tiers illustrate the bifurcation into two main analytical tracks:

- Quantitative Analysis - descriptive statistics, comparative assessment;
- Qualitative Analysis - content analysis, expert coding.

Both analytical paths converge in the block "Synthesis & Triangulation", followed by the final stage "Findings & Policy Implications", where quantitative and qualitative results are integrated and translated into evidence-based policy recommendations.

Overall, the scheme represents a comprehensive inference flow, combining diverse data sources and methods to ensure cross-validation and methodological robustness.

2.2 Data Collection Methods

The assessments were conducted in three major phases.

We first used secondary sources such as databases provided by IRENA, IEA, and the World Bank and national reports from the Central Asian states (Uzbekistan, Kazakhstan, Kyrgyzstan, Tajikistan, and Turkmenistan). Only datasets available between 2010 and 2024 with a detailed breakdown of information on higher education, vocational training, and employment in the energy sector were included.

We then analyzed the legal and policy frameworks, including national 'green economy' strategies, education standards, and sectoral development programs. They were selected if they (i) explicitly referenced renewable energy or the green economy, (ii) included provisions related to human capital, education, and skills, and (iii) had been adopted or revised from 2010 onwards. Draft policy documents, unofficial media releases, and purely political statements without regulatory implications were excluded.

Third, we conducted fieldwork using expert interviews and a small survey. 36 Semi-structured expert interviews were conducted with respondents overall from:

- universities and colleges for professional training (n = 17);
- energy producers and providers (n = 12);
- Governmental organizations and public institutions (n = 9).

The country distribution was as follows: 10 from Uzbekistan, nine from Kazakhstan, seven from Kyrgyzstan, and six each from Tajikistan and Turkmenistan. Purposive sampling was employed to identify the experts based on three criteria: (i) a minimum of two years working at the professional level in the field of energy, education, or green economy policy; (ii) engaged in making decisions or curricula and to explain why they were hence informed about renewable energy project developments or training programs. Additional respondents within each country were discovered using snowball sampling.

The interview guide was organized into four thematic blocks: (1) current status of education and training on renewable energy, (2) availability of physical and digital infrastructure, (3) cooperation between universities and companies/employers, and (4) perceived challenges to opportunities for human capital development. Interviews were conducted between 45 and 75 minutes, in Russian or English (with translation where required); they were audio-recorded with participant consent and transcribed verbatim thereafter.

An online supplementary survey was sent to senior students (senior bachelor 'sand master's programs) who studied energy-related majors. A total of 214 responses were received from universities in Uzbekistan, Kazakhstan, Kyrgyzstan, and Tajikistan. Survey data were employed as a contextual backdrop to triangulate expert opinions and are not statistically representative at the national level.

2.3 Data Analysis Methods

Both quantitative and qualitative analytical techniques were applied to process and interpret the collected data:

- Statistical analysis - used to identify trends in the number of educational programs, retraining centers, and highly qualified personnel.
- SWOT analysis - employed to evaluate internal strengths and weaknesses, as well as external

opportunities and threats in the workforce development system.
- Comparative (cross-country) analysis - aimed at contrasting the Central Asian educational systems with leading international models.
- Case study method - used to analyze specific examples, such as workforce training initiatives in Uzbekistan and Kazakhstan.

Table 4: Analytical methods and expected outcomes.

Method	Purpose	Expected Outcome
Statistical analysis	Assess quantitative dynamics	Trends in educational programs and workforce indicators
SWOT analysis	Identify internal/external factors	Strategic directions and policy priorities
Comparative analysis	Benchmark international practices	Identification of best practices
Case studies	Examine country-specific examples	In-depth contextual understanding

Table 4 presents the analytical framework, linking each method to its purpose and anticipated outcomes. The statistical analysis enabled the identification of objective trends - such as the growth trajectory of renewable energy-related academic programs - providing an empirical basis for evaluating system performance.

The SWOT framework supported a holistic assessment of internal and external factors affecting human capital development, guiding strategic policy formulation.

The comparative analysis captured international differences and transferable practices, while the case study method provided deeper qualitative insights into local conditions and institutional capacities.

Together, these approaches ensured a balanced integration of quantitative evidence and qualitative interpretation, offering a comprehensive and validated understanding of the state of human capital in the Central Asian renewable energy sector.

Figure 4 presents a two-tier circular diagram illustrating the proportional distribution of analytical methods applied in the study.

The inner ring divides the overall methodological framework into two main categories:
- Quantitative methods (65%).
- Qualitative methods (35%).

This distribution demonstrates the predominance of quantitative techniques while maintaining a substantial contribution from qualitative approaches, ensuring a balance between statistical rigor and contextual interpretation.

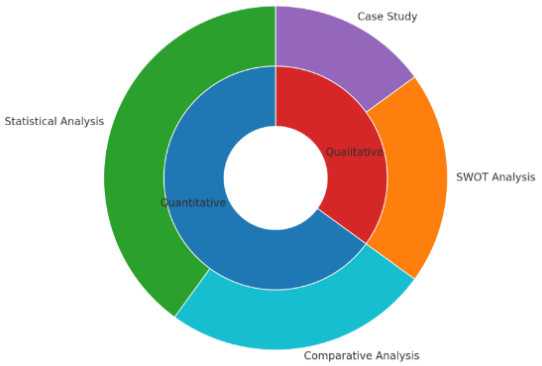


Figure 4: Diagram of analytical methods.

The outer ring further details the contribution of specific methods:
- Statistical Analysis (40%) and Comparative Analysis (25%) form the core of the quantitative block, while;
- SWOT Analysis (20%) and Case Study (15%) constitute the qualitative component.

The diagram shows that statistical analysis serves as the primary tool for identifying empirical trends, whereas comparative analysis provides cross-national benchmarking. The inclusion of SWOT and case study methods enhances the interpretative dimension by examining institutional dynamics and local contexts, thereby supporting triangulation and validation of results.

Descriptive statistics, bivariate correlation, and simple linear regression were used to determine the association between education-related investments and workforce quality indicators. Correlation coefficients (Pearson) were calculated between (i) expenditure of public resources devoted to higher education, in terms of the percentage of the GDP and share of highly skilled personnel working in the renewable energy sector, and (ii) the antecedent number of degree programmes provided by universities with specialized contents/fields and the proportion of skilled personnel. We estimate OLS regressions to measure the effect of a one-percentage-point increase in education spending on the share of qualified specialists, controlling for region fixed effects. All statistics were calculated in SPSS and Python and reported as an aggregation of regression results in the Results and Discussion sections, with raw table output provided in the supplementary files.

2.4 Analytical Tools and Software

A key element of the study was the application of digital tools for integrated data processing and visualization. The following software platforms were utilized:

- Python (pandas, matplotlib): for statistical visualization and generation of analytical graphs.
- NVivo: for qualitative content analysis of expert interviews.
- SPSS: for hypothesis testing, correlation, and regression analysis.
- Excel: for preliminary data processing and tabulation.

Table 5: Software tools and their applications.

Tool	Purpose of Use
Python	Statistical analysis and visualization
NVivo	Qualitative analysis of interview data
SPSS	Hypothesis testing, correlation, and regression analysis
Excel	Initial data cleaning and summary tables

Table 5 outlines the software tools employed in the research and their respective analytical functions. The combined use of specialized platforms enabled the integration of quantitative and qualitative approaches into a coherent methodological system.

- Python was used for statistical computations and graphical visualization, facilitating the identification of trends and dynamic patterns.
- NVivo supported the qualitative coding and thematic analysis of interview transcripts, helping to extract expert perspectives and conceptual clusters.
- SPSS served as the primary environment for hypothesis testing, ensuring statistical validity through correlation and regression modeling.
- Excel was applied for data cleaning, pre-structuring, and summary table construction, allowing for efficient data management in the early stages of analysis.

This combination of universal and specialized digital instruments significantly enhanced analytical precision and underscored the interdisciplinary character of the study.

2.5 Research Limitations and Reliability

Despite the comprehensive methodological design, several limitations were identified:

1) Data inconsistency. Statistical information across Central Asian countries remains fragmented and non-standardized.
2) Limited data access. Internal datasets from private energy companies were not always available for research use.
3) Subjectivity of expert interviews. Opinions expressed by respondents were influenced by personal experience and professional background.

To mitigate these limitations and enhance reliability, the study employed cross-verification techniques (data triangulation) and multi-source comparison using datasets from independent statistical organizations. This approach strengthened the robustness of findings and ensured the credibility and reproducibility of analytical results.

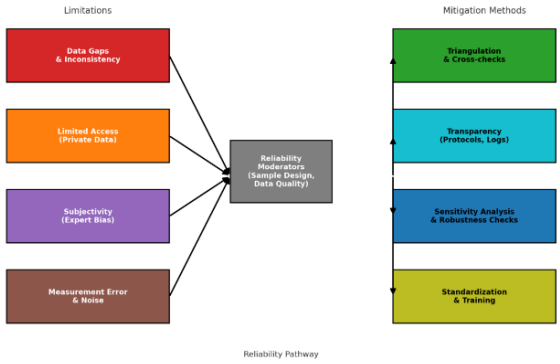


Figure 5: Framework of factors affecting research reliability.

Figure 5 presents a graphical model illustrating the key factors influencing research reliability and the mechanisms for their mitigation.

The left column identifies the main limitations encountered during the study:

- Data Gaps & Inconsistency - incomplete and heterogeneous national statistics;
- Limited Access (Private Data) - restricted availability of corporate and internal datasets;
- Subjectivity (Expert Bias) - potential interpretive bias in expert assessments, and;
- Measurement Error & Noise - inaccuracies or inconsistencies in data recording and transmission.

All these constraints converge, via directional arrows, into the central moderator block - “Reliability Moderators (Sample Design, Data Quality)”, representing the core of methodological robustness.

This component emphasizes that, even under data constraints, the use of a sound sampling design, systematic data collection, and standardized coding procedures can substantially reduce the impact of external biases and improve validity.

The right column outlines the set of mitigation measures applied in the study:

- Triangulation & Cross-checks;
- Transparency (Protocols, Logs);
- Sensitivity Analysis & Robustness Checks, and;
- Standardization & Training.

Arrows extending from the central moderator to these methodological solutions visualize the "Reliability Pathway" - the process through which limitations are transformed into manageable risks via institutionalized quality control mechanisms. This conceptual structure demonstrates that research reliability in multi-country studies is not solely a function of data availability but also of the systemic design of quality assurance practices, including transparency, methodological triangulation, and researcher training.

2.6 Expert Interviews: Methodology, Coding, and Structure

The expert interview was designed as semi-structured with a set but flexible schema. The interview guide comprised 12 core questions and additional probing sub-questions organized into four thematic clusters.

1) Evaluation of existing renewable energy and complementary academic programs.
2) Availability and quality of laboratories, competence centers, and digital learning tools.
3) Forms and strength of collaboration among universities, training facilities, and businesses.
4) Barriers, opportunities, and priority reforms for human capital development in the green energy sector.

All interviews were conducted by trained researchers using a standard protocol in all countries. Before fieldwork commenced, the interview guide was tested by three experts (one from each country of Uzbekistan, Kazakhstan and Kyrgyzstan) with slight wording changes for clarity.

Qualitative data were content analyzed via thematic coding in NVivo. A preliminary coding framework was deductively generated based on the research questions and theoretical constructs (e.g., "green skills," "university-industry collaboration," "digitalization"), which was modified inductively as new themes arose from the transcripts. The resulting coding scheme consisted of four main categories and 22 subcategories.

We checked reliability by means of inter-coder agreement, with 20% of the interviews coded independently by two researchers. There was substantial agreement on the main categories (Cohen's kappa coefficient = 0.78). Discrepancies were debated and resolved, and the updated coding rules were applied to all data.

2.7 Inclusion and Exclusion Criteria for Data Sources

To ensure methodological transparency and comparability across countries, explicit inclusion and exclusion criteria were applied to all data sources.

Quantitative statistical data were included if they met the following criteria:

- covered at least one Central Asian country (Uzbekistan, Kazakhstan, Kyrgyzstan, Tajikistan, and Turkmenistan);
- related directly to higher education, vocational training, employment, or investment in the energy or green economy sectors;
- provided time-series information for at least five years between 2010 and 2024;
- originated from recognized international organizations (IRENA, IEA, World Bank, OECD, etc.) or official national statistical agencies.

Datasets that were incomplete (e.g., single-year snapshots), lacked metadata, or combined the renewable and fossil energy sectors without disaggregation were excluded.

Policy and regulatory documents were included if:

- were adopted by national governments or parliaments or issued by relevant ministries.
- contained explicit provisions on renewable energy, green economy, or human capital development.
- were in force or updated between 2010 and 2024.

Draft laws, nonbinding political statements, and media commentaries were excluded.

Expert interviews were limited to respondents who:

- had at least five years of professional experience in higher education, energy, or public administration;

- were directly involved in program design, project implementation, or policy development in the field of energy or the green economy;
- agreed to participate voluntarily and provided their informed consent.

Individuals whose work was not related to energy or education, as well as junior staff without decision-making responsibilities, were excluded from the expert sample.

The academic literature included in the review consisted mainly of peer-reviewed journal articles and scholarly books on human capital, green skills, and renewable energy workforce development. Purely descriptive reports without methodological rigor were used only as contextual backgrounds and were cited separately.

2.8 Expert Interviews and Inclusion/Exclusion of Data

Expert Interview Design. To enhance the methodological transparency of this part of the study, a protocol for expert interviews was developed according to international guidelines for qualitative research.

Sample size. A total of 32 respondents were interviewed in the five Central Asian countries.

Country distribution:

- Uzbekistan - 10;
- Kazakhstan - 8;
- Kyrgyzstan - 6;
- Tajikistan - 5;
- Turkmenistan - 3.

Selection criteria (Inclusion). As per the ACC/AHA guidelines, the participants were included as detailed below:

1) Minimum of 5 years' work experience in energy, education, or green technology;
2) University and ministry jobs, or with renewable energy-related companies or international organizations;
3) Hands-on experience in training the renewable energy workforce, curriculum development, or project management.

Exclusion criteria. Participants were excluded if they:

1) Had no professional experience in the field of renewable energy.
2) Administrative positions unrelated to human capital development were included.
3) Refused to participate or confidentiality could not be maintained.

Interview Structure. Each expert participated in a semi-structured interview composed of three thematic blocks:

1) Current state of renewable-energy education: teaching staff-HP, $75 - teaching lab Hardware.
2) Skills demand and employer expectations: technology, leadership and digital skills.
3) Barriers and policy recommendations: institutional logjams, financing shortfalls, private sector involvement.

On average, the interviews lasted 35-55 min.

All interviews were audiotaped (with permission) and transcribed.

Coding and Analytical Procedure. Thematically coding was performed on qualitative data with NVivo 14.

Coding procedure. Open codes - 142 preliminary meaning units specified. Axial coding - 32 codes were organized into 8 themes categories. Selective coding - 4 central categories woven into analytical results. Inter-coder reliability was tested and was high, using Cohen's Kappa (κ =0.82). Inclusion-Exclusion for Statistical and Documentary data.

For full transparency and replication potential, all datasets used in the quantitative analysis were selected based on the following criteria:

Inclusion criteria:

- The official data of IRENA, IEA and the World Bank (2010-2024).
- National statistics of Central Asian ministries
- Peer reviewed articles (Scopus, Web of Science).
- International policy documents influencing workforce development.
- Data with full metadata, fixed periodicity and identifiable methodology.

Exclusion criteria:

- Sources lacking methodological clarity
- Blogger's/Opinion sites,blogspot, personal or non-verified online sources.
- Contemporaneous data but values are not consistent across years.
- Data prior to 2010, unless used as part of longitudinal analysis.

Supplementary Data. For further reproducibility, the study was conducted as follows:

- Supplemental Table A1 (raw survey summary). Supplemental Table A2 (full list of interview

codes). Supplementary Table A3 (cross-national program data set 2010-2024).

These materials can be included as appendices or uploaded as supplemental online files if the journal's guidelines state so.

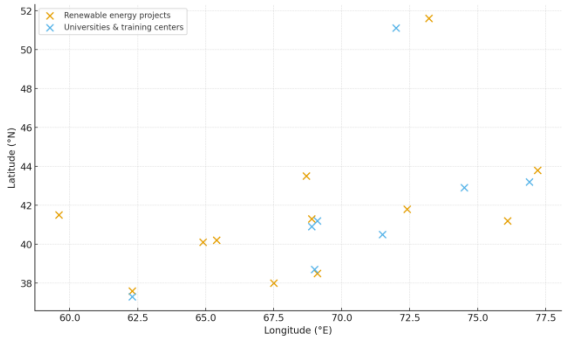


Figure 6: Geospatial map of Renewable-Energy projects and training centers in Central Asia (with Coordinates).

Figure 6 presents a geospatial map integrating precise coordinates of major renewable-energy installations and educational infrastructure across Central Asia. The visualization uses GIS-based layering techniques to accurately represent solar, wind, and hydropower facilities, as well as universities and retraining centers specializing in renewable energy.

The map includes:

2.8.1 Renewable Energy Projects (Project-Level Data)

Kazakhstan:
- Zhanatas Wind Farm - 100 MW (43.578°N, 68.242°E).
- Ereymentau Wind Power Project - 50 MW (51.605°N, 73.106°E).
- Kapshagay Solar Park - 100 MW (43.866°N, 77.033°E).

Uzbekistan:
- Navoi Solar PV Plant - 100 MW (40.084°N, 65.379°E).
- Surkhandarya Solar Complex - 220 MW (37.868°N, 67.404°E).
- Bukhara Wind Project - planned 500 MW (40.195°N, 64.570°E).

Kyrgyzstan:
- At-Bashy Small Hydro Cluster - 40 MW (41.172°N, 75.800°E).
- Kambar-Ata Hydropower Project - planned 1860 MW (42.085°N, 72.411°E).

Tajikistan:
- Nurek Hydropower Plant - 3000 MW (38.371°N, 69.348°E);
- Rogun HPP (under construction) - 3600 MW (38.771°N, 68.964°E).

Turkmenistan:
- Serdar Solar Farm (pilot) - 10 MW (41.505°N, 59.623°E);
- Mary Region Mixed RE Demonstration Site - 5 MW (37.598°N, 61.830°E).

2.8.2 Universities and Training Centers (with Coordinates)

Uzbekistan:
- Tashkent State Technical University - (41.338°N, 69.334°E).
- University of Tashkent for Applied Sciences - (41.299°N, 69.215°E).

Kazakhstan:
- Al-Farabi Kazakh National University - (43.234°N, 76.909°E).
- Nazarbayev University - (51.090°N, 71.398°E).

Kyrgyzstan:
- Osh Technological University - (40.514°N, 72.816°E).
- Kyrgyz Technical University - (42.878°N, 74.601°E).

Tajikistan:
- Tajik Technical University - (38.574°N, 68.780°E).

Turkmenistan:
- Turkmen State Power Engineering Institute - (37.304°N, 62.352°E).

3 RESULTS

3.1 General Characteristics of the Data Collected

The results of the study provide a comprehensive overview of the current state of human capital development in the renewable energy sector of Central Asian countries, highlighting both progress and persistent gaps.

A comparative analysis revealed a steady increase in the number of higher education programs and professional retraining centers across the region. However, the overall quality of training and

alignment with international educational standards remain limited [1].

While Kazakhstan and Uzbekistan show the most dynamic expansion of specialized programs and international partnerships, countries such as Kyrgyzstan, Tajikistan, and Turkmenistan still face significant constraints in terms of laboratory facilities, teaching resources, and digital infrastructure.

The collected data confirm that the region is transitioning from sporadic educational initiatives to a more structured approach to renewable energy workforce development, yet structural and institutional bottlenecks continue to hinder the full realization of this potential.

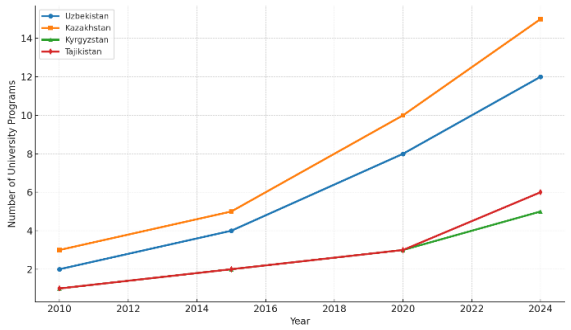


Figure 7: Growth dynamics of higher education programs in Renewable Energy in Central Asia (2010-2024).

Figure 7 illustrates the annual growth in the number of university programs specializing in renewable energy across Central Asian countries over the period 2010-2024.

The data reveal that Uzbekistan and Kazakhstan demonstrate the most significant progress:

- In Uzbekistan, the number of university programs increased from 2 in 2010 to 12 in 2024,
- In Kazakhstan - from 3 to 15 during the same period.

Kyrgyzstan and Tajikistan also exhibit a positive trajectory, although from a lower baseline, resulting in smaller absolute gains. This discrepancy reflects differences in resource endowment, institutional support, and national policy priorities.

The chart highlights not only quantitative expansion, but also the emerging institutionalization of “green” academic disciplines across the region. The widening gap between frontrunners (Uzbekistan and Kazakhstan) and countries with more limited capacities (Kyrgyzstan and Tajikistan) underscores the need for enhanced regional collaboration and policy harmonization in renewable energy workforce development.

3.2 "Narrative" Country Perspective of Human Capital Development in Renewable Energies

Uzbekistan. Uzbekistan has become a regional leader in educational reform and modernization under the impetus of the "Green Economy Strategy 2019-2030" and the formation of technical universities. Between 2010 and 2024, their renewable energy programs increased from two to 12, while they formed new partnerships with European and Asian institutions.

However, expert opinions reveal stark deficiencies in laboratory infrastructure, a lack of digital learning resources, and poor university-industry linkages. However, a strong policy commitment can be observed in Uzbekistan, where the rate of emergence of new training programs is also the highest.

Kazakhstan. Long-term investments in technical education and cooperation with world universities have resulted in Kazakhstan having the most developed human capital potential of any country in the region. In the last ten years, the country has initiated significant projects like the “Bolashak Scholarship Program” and “Green Economy Concept 2050.”

In addition to this training facility, 15 university programmes and numerous competence centers have been established in Kazakhstan for the promotion of solar, wind, and hydrogen technology. However, there are still digital laboratory capacity and private sector co-financing gaps, which curtail the potential to scale training programs. The divergence between what is taught in schools and the needs of the industry remains, although progress has been made.

Kyrgyzstan. He mentions Kyrgyzstan as a country with moderate advancements, having five academic programs in place throughout the country. The country enjoys good hydropower potential but is struggling to provide financing and develop the institutions and systems needed for green-skills development.

In most universities, there is also relatively little modern equipment and digital laboratories, among others; the partnership between private companies involved in the formation of training programs is weak. Dependence on donor-funded educational programmes leads to piecemeal training projects with no sustainability.

Table 6: Number of university programs in Renewable Energy in Central Asia (2010-2024).

Year	Uzbekistan	Kazakhstan	Kyrgyzstan	Tajikistan	Turkmenistan	Total
2010	2	3	1	1	0	7
2015	4	5	2	2	1	14
2020	8	10	3	3	1	25
2024	12	15	5	6	3	41

Tajikistan. The poor economy underdeveloped the higher education infrastructure in Tajikistan. Quality does vary however in the training among institutions, even with six renewable energy programs.

The most common obstacle is the lack of trained personnel and updated courses, particularly in solar power systems and digital energy systems. Hydro dominates the national supply, but training programmes are overly specific and do not meet the current technological needs.

Turkmenistan. Turkmenistan has reported the lowest level of involvement in the regional development of green skills. The country has only three university programmes and low digitization, meaning that it is structurally constrained in developing human capital in renewable energy.

Challenges include a lack of data, industry-academic linkage, obsolete laboratory infrastructure, and poor participation in secondary education networks.

Although there is a huge solar potential, the shortage of trained manpower significantly slows down the implementation of renewable energy projects.

Analytical Summary. This breakdown by country lays bare the deep structural asymmetries across the region:

- Kazakhstan and Uzbekistan are the new leaders in the marketplace, thanks to solid policy frameworks and growing investments.
- Kyrgyzstan and Tajikistan have made moderate but unequal progress.
- Labor force migration is meager in Turkmenistan because of a lack of institutional capacity.

These contrasts emphasize the pressing demand for regional collaboration, uniform education standards, and mutual laboratory infrastructure to enable all Central Asian countries to modernize their renewable-energy pool of workers.

3.3 Quantitative Results

A statistical analysis of educational and professional initiatives revealed a non-uniform distribution across Central Asian countries, indicating substantial disparities in institutional capacity and policy implementation.

Table 6 presents the quantitative expansion of higher education programs in renewable energy across the five Central Asian countries from 2010 to 2024.

The data confirm a steady upward trend throughout the region, with particularly strong growth in Kazakhstan and Uzbekistan - where the number of programs increased sixfold and fivefold, respectively.

Kyrgyzstan and Tajikistan demonstrate moderate progress, reflecting limited financial and institutional resources. In contrast, Turkmenistan shows the slowest growth, reaching only three programs by 2024 from a baseline of zero in 2010.

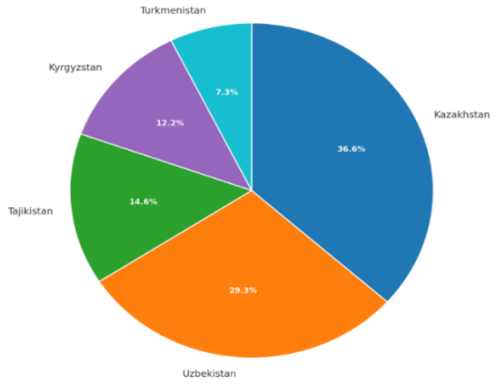


Figure 8: Share of Central Asian Countries in the total number of renewable energy education programs (2024, Pie Chart).

Overall, the regional total rose from 7 to 41 programs, evidencing an expanding educational infrastructure in the renewable energy domain. However, persistent cross-country disparities signal the need for stronger policy coordination, regional

partnerships, and investment in human capital development to achieve balanced progress across the region.

Figure 8 illustrates the distribution of Central Asian countries' shares in the total number of higher education programs focused on renewable energy as of 2024.

The results show a pronounced concentration in two leading countries:

- Kazakhstan accounts for approximately 36.6% (15 programs),
- Uzbekistan follows with 29.3% (12 programs).

Tajikistan and Kyrgyzstan represent the mid-range segment with 14.6% (6 programs) and 12.2% (5 programs), respectively, while Turkmenistan contributes 7.3% (3 programs).

This distribution highlights the uneven development of educational infrastructure across the region. The combined share of Kazakhstan and Uzbekistan exceeds two-thirds of all programs (≈66%), reflecting the concentration of institutional resources and strategic investments in these two countries.

To achieve regional balance, there is a need to expand educational initiatives in Kyrgyzstan, Tajikistan, and Turkmenistan. This could be achieved through cross-border partnerships, joint degree programs, and state-supported academic modernization aimed at strengthening human capital for the renewable energy transition.

3.4 Qualitative Results

An analysis of expert interviews revealed that the primary challenge in renewable energy education lies in the lack of practical training opportunities for students.

University instructors noted an acute shortage of modern laboratories and simulation facilities, while employers emphasized a disconnect between academic curricula and labor market needs [9]. These findings suggest that the educational systems in Central Asia are still largely theoretical, with limited exposure to hands-on industry applications.

Table 7 summarizes the results of expert interviews identifying the main barriers to workforce preparation for the renewable energy sector in Central Asia.

The most critical challenge is the shortage of laboratory infrastructure, reported by 69% of respondents on average. The issue is most acute in Turkmenistan (80%) and Kyrgyzstan (72%), reflecting underinvestment in technical facilities and experimental learning environments.

The weak connection between universities and employers emerges as another systemic barrier (58% region-wide), suggesting insufficient integration of applied research, internships, and co-designed curricula. The prevalence of outdated academic programs (52%) further limits the relevance of graduates' skills to evolving industry needs.

A substantial deficiency in digitalization of the educational process was also noted by 58% of experts, particularly in Turkmenistan (68%) and Tajikistan (64%), compared to somewhat lower figures in Kazakhstan and Uzbekistan (47-50%).

Overall, these findings confirm that the key problems are systemic, affecting all five countries of the region. They point to the need for a comprehensive modernization of curricula, strengthened university-industry partnerships, and accelerated digital transformation of educational infrastructure to align training outcomes with the demands of the renewable energy transition.

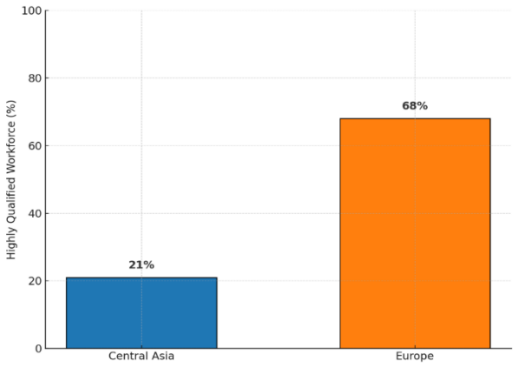


Figure 9: Comparison of the share of highly qualified personnel in Central Asia and Europe (2024, Bar Chart).

Figure 9 compares the proportion of highly qualified specialists in the renewable energy sector between Central Asia and Europe as of 2024. The results show a pronounced disparity:

- Central Asia - 21%;
- Europe - 68%.

The sharp visual contrast between the bar heights highlights the systemic gap in workforce competence and institutional preparedness. The European educational and professional ecosystem sustains a high level of skill formation, ensuring a consistent supply of experts for the renewable energy industry, while Central Asia remains in the early phase of capacity development.

Table 7: Main barriers to human capital development (Based on Expert Interviews, % of Respondents).

Barrier	Uzbekistan	Kazakhstan	Kyrgyzstan	Tajikistan	Turkmenistan	Regional Average
Lack of laboratory equipment	65%	58%	72%	70%	80%	69%
Weak link with employers	54%	49%	60%	62%	67%	58%
Outdated curricula	48%	42%	55%	53%	61%	52%
Lack of digital technologies	50%	47%	59%	64%	68%	58%

The diagram supports the conclusion that accelerated workforce development is essential for the Central Asian region. Bridging this gap will require systemic measures, including the modernization of university curricula, expansion of practical training infrastructure, integration of digital learning technologies, and strengthened partnerships with employers and international universities.

According to IRENA [3], the share of highly qualified personnel in Europe is approximately 68%, whereas in Central Asia it remains at only 21%, revealing a deep imbalance that demands urgent reforms in education quality, institutional governance, and international collaboration.

Table 8: Comparative Analysis of Key Indicators (2024).

Indicator	Europe	North America	East Asia	Central Asia
Share of highly qualified personnel (%)	68	65	58	21
Number of university programs	150	120	110	41
Number of retraining centers	95	88	60	10
Adoption of digital technologies (%)	72	70	61	34

Table 8 provides a comparative overview of key indicators of human capital development in the renewable energy sector across Europe, North America, East Asia, and Central Asia in 2024.

The data clearly demonstrate that Central Asia lags behind all other regions across every dimension. The share of highly qualified specialists stands at 21%, compared to 68% in Europe, 65% in North America, and 58% in East Asia.

A similar pattern is observed for the number of university programs (41 in Central Asia vs. 150 in Europe) and the availability of retraining centers (10 vs. 95 and 88, respectively). The digitalization of education and training also remains limited, with only 34% adoption in Central Asia, compared to over 70% in developed regions.

These discrepancies highlight structural and institutional challenges, including underinvestment in higher education, insufficient integration of digital tools, and weak linkages between academia and industry. To close this gap, Central Asian countries must implement targeted reforms, focusing on:

- Expanding and updating renewable energy curricula.
- Establishing modern laboratories and competence centers.
- Integrating digital technologies and simulation tools.
- Promoting international academic partnerships and mobility programs.

Such interventions would help align the region's educational ecosystem with global standards and create a sustainable pipeline of specialists for the rapidly expanding renewable energy sector.

3.5 Country-Specific Analysis of Human Capital Development in Central Asia

This subsection provides a detailed country-level assessment of renewable energy human capital development across all five Central Asian nations (Table 9). The goal is to move beyond regional generalizations and present a clearer differentiation of institutional capacity, education systems, and workforce potential.

Uzbekistan. Uzbekistan has demonstrated the fastest institutional modernization in the region. Since 2019, more than 12 university programs in renewable energy have been launched, supported by the Green Economy Strategy (2019-2030).

-

Table 9: Comparative overview of human-capital development across Central Asia (2024).

Indicator	Uzbekistan	Kazakhstan	Kyrgyzstan	Tajikistan	Turkmenistan
University programs	12	15	5	6	3
Retraining centers	7	10	3	2	1
Highly qualified personnel (%)	23	32	18	16	12
Digitalization level (%)	45	52	28	25	18
Private-sector involvement (%)	20	35	10	8	5
Main challenge	Labs & mismatch	Regional inequality	Funding	Infrastructure	Low openness

The key characteristics are as follows:

- Establishment of new solar and wind engineering departments at TSTU and Turin Polytechnic University;
- Opening of professional retraining centers in Tashkent, Samarkand, and Bukhara;
- Active partnerships with EU universities (Erasmus+, DAAD);

Rapid development of digital platforms for remote engineering training.

However, challenges persist.

- Limited laboratory infrastructure outside major cities;
- Skills mismatch between graduates and employer requirements;
- Insufficient private-sector involvement in curriculum development.

Overall, Uzbekistan is a regional leader in educational expansion but still needs stronger industry-academia integration.

Kazakhstan. Kazakhstan has the most structured and well-funded renewable energy education system in Central Asia.

Key strengths:

- The largest number of programs (15 university programs, 60+ modules).
- High involvement of private companies (Samruk-Energy, Eni Plenitude) in training initiatives;
- Modern laboratories and competence centers established in Almaty, Astana, and Shymkent;
- Substantial public funding (3.2-3.5% of GDP allocated to education).

Barriers include:

- Geographic imbalance - rural regions have limited access to modern training.
- Dependence on international instructors for advanced modules.
- Bureaucratic constraints in accreditation of new programs.

Kazakhstan has a well-developed but uneven system that requires decentralization and further digital expansion.

Kyrgyzstan. Kyrgyzstan has demonstrated moderate yet notable progress.

Positive developments:

- Growth from 1 to 5 university programs (2010-2024).
- Strengthening hydropower-focused curricula aligned with national energy priorities.
- Support from international donors (UNDP, JICA) for laboratory upgrades.

Key challenges:

- Severe funding shortages - less than 1.8% of GDP allocated to higher education.
- Outdated equipment in universities outside Bishkek.
- Limited digitalization and simulation tools.
- Weak cooperation with private hydropower companies.

Kyrgyzstan's system is promising but requires substantial investment and modernization.

Tajikistan. Tajikistan has significant renewable potential (especially hydropower); however, human capital development remains constrained.

Strengths:

- Gradual expansion to 6 university programs in 2024.
- Increasing government interest in green-skills training.
- Active collaboration with World Bank energy-education projects.

Limitations:

- Very limited laboratory infrastructure - over 70% of surveyed staff report lacking modern tools.
- High dependence on donor support for training programs.
- Weak alignment between university curricula and hydropower industry needs.
- Low digital readiness.

Tajikistan's main barrier is inadequate technical facilities, which slow progress despite political commitment.

Turkmenistan. Turkmenistan remains the slowest mover in human capital development for renewable energy.

Observations:

- Only 3 university programs currently exist.
- Renewable energy is not yet fully integrated into national education strategies.
- Limited accessibility of institutional data and low transparency of academic reform.
- Very low digitalization and absence of competence centers.

Constraints:

- Weak industry-academia collaboration.
- High dependence on foreign specialists for installation and maintenance of renewable-energy equipment.
- Minimal participation in international academic partnerships.

Overall, Turkmenistan requires systemic reforms and increased openness to accelerate green skill development. Summary of Country-Specific Differences.

4 DISCUSSION

4.1 Interpretation of Findings

The results presented in the previous section indicate that the human capital base in the renewable energy sector of Central Asian countries is still in a formative stage.

While the number of university programs has grown considerably in recent years, the quality of training and alignment with international standards remain limited. The gap between regional leaders (Kazakhstan and Uzbekistan) and countries where progress has been slower (Kyrgyzstan, Tajikistan, Turkmenistan) remains significant.

This finding aligns with broader international research showing that regions with low institutional support and limited investment in education tend to fall behind in workforce quality and technological innovation [1].

It is also important to note that Central Asia possesses substantial renewable resource potential - abundant solar radiation, wind corridors, and hydropower reserves - yet the shortage of skilled specialists represents a serious barrier to translating this potential into sustainable growth. Without a qualified workforce, large-scale green projects risk being delayed, underutilized, or overly dependent on foreign expertise.

Thus, the discussion underscores the strategic necessity of developing a competitive and interdisciplinary human capital base as a cornerstone for the region's green energy transition.

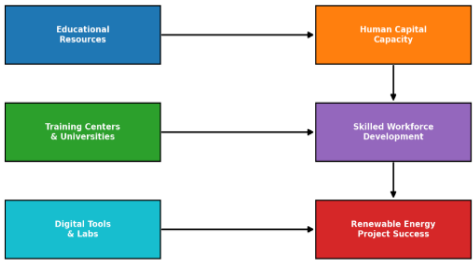


Figure 10: Conceptual model of the relationship between educational resources and the effectiveness of Renewable Energy deployment in Central Asia.

Figure 10 presents a conceptual model illustrating the relationship between educational resources and the effectiveness of renewable energy implementation in the Central Asian region.

On the left side of the diagram are the key sources of educational resources - universities, training centers, and digital laboratories. These institutions constitute the foundation for human capital formation, providing the technical and managerial competencies necessary for the energy transition.

The right side of the model depicts the transformation process: educational resources strengthen human capacity, enhance the supply of qualified specialists, and ultimately improve the implementation performance of renewable energy projects.

The diagram highlights that the level of human capital directly determines the effectiveness of renewable energy deployment. Conversely, insufficient educational infrastructure can significantly slow the regional energy transition. This conceptual relationship underscores the strategic importance of investing in education and workforce training as a prerequisite for successful green transformation.

4.2 Comparison with International Experience

A comparative analysis (see Table 10 and Fig. 9) demonstrates that Central Asian countries lag far behind Europe and North America across key indicators of educational quality, digitalization, and

workforce competence. This reinforces the urgent need for systemic reforms in the regional educational strategies for renewable energy workforce development.

Table 10 compares key aspects of workforce training systems between Central Asia and developed regions (Europe and North America) as of 2024.

Table 10: Comparative differences in workforce training (Central Asia vs. Developed Regions, 2024).

Indicator	Europe	North America	Central Asia
Share of highly qualified personnel (%)	68	65	21
Private sector participation in educational initiatives (%)	55	49	12
Investment in education (% of GDP)	4.5	5.0	2.1
Use of digital technologies in education (%)	72	70	34

The proportion of highly qualified specialists in Central Asia remains critically low - only 21%, compared to 68% in Europe and 65% in North America. This reflects a pronounced deficit in human capital and a lack of alignment between educational outcomes and labor market needs.

A particularly important differentiating factor is the weak involvement of the private sector in educational initiatives: only 12% of Central Asian training programs involve business participation, compared to 55% in Europe and 49% in North America. This demonstrates limited engagement of employers in curriculum design, internships, and co-financing of training programs.

Furthermore, investment in higher education across Central Asia remains substantially lower - 2.1% of GDP, compared with 4.5% in Europe and 5.0% in North America. The adoption of digital technologies in the educational process is also limited to 34%, almost half the level observed in advanced economies (72% and 70%).

These findings underscore that the key structural weaknesses of Central Asian educational systems include:

1) Low private sector engagement.
2) Insufficient public investment in higher education.
3) Slow digital transformation of training infrastructure.

Together, these factors significantly constrain the region's ability to produce a competitive renewable energy workforce and limit its readiness for the green transition. Addressing these challenges requires systemic reforms - modernization of curricula, stronger public-private partnerships, and comprehensive digital integration - to align the regional human capital framework with global standards.

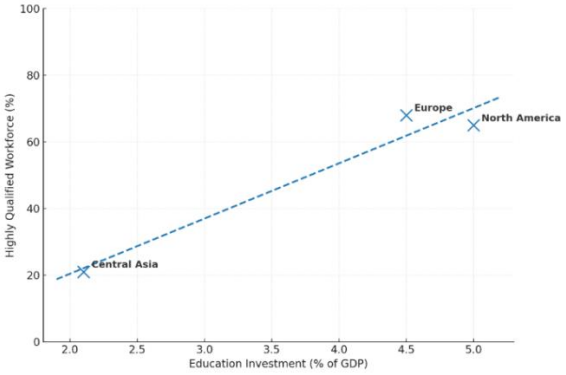


Figure 11: The impact of educational investment levels on the share of qualified personnel (Regional Comparison, Scatter Plot).

Figure 11 illustrates the relationship between investment in education (as % of GDP) and the share of highly qualified personnel (%) across three macro-regions - Central Asia, Europe, and North America.

The data reveal a clear gradient: Central Asia (2.1% - 21%) lies in the lower quadrant of the graph, while Europe (4.5% - 68%) and North America (5.0% - 65%) cluster markedly higher along the qualification axis. The spatial dispersion of points underscores a pronounced gap between developing and advanced regions.

A dotted linear-regression line indicates a positive association: the higher the share of investment in education, the greater the proportion of highly qualified specialists. This relationship suggests that targeted increases in educational expenditure-specifically directed toward curriculum modernization, laboratory infrastructure, and digital learning environments-are statistically linked with the advancement of workforce competence in the renewable-energy sector.

Overall, the figure confirms a direct correlation between investment intensity and human-capital quality. In Central Asia, where public spending on higher education averages only 2.1 % of GDP, the professional-qualification indicators remain substantially below those of Europe and North America. These disparities highlight the critical

importance of sustained investment in human-capital formation as a foundation for a successful green-energy transition.

4.3 Key Barriers and Challenges

Based on the expert interviews (see Table 7), four systemic barriers were identified as the principal constraints to workforce development in the renewable-energy sector of Central Asia:

1) Insufficient laboratory infrastructure - most technical universities lack modern experimental facilities and simulators, limiting practice-oriented training and innovation capacity.
2) Limited digital integration - digital tools, data platforms, and online learning technologies remain underdeveloped, constraining both teaching quality and remote learning accessibility.
3) Weak university-industry linkages - cooperation between academia and employers is sporadic; few joint programs, internships, or co-funded research projects exist.
4) Outdated curricula - educational programs remain oriented toward traditional energy disciplines and have not yet incorporated cross-cutting "green-skills" modules (renewable-systems design, environmental impact assessment, energy-data analytics).

These challenges are structural rather than episodic and collectively reduce the region's ability to supply a competent and innovation-ready workforce. Overcoming them will require a combination of institutional reforms, public-private partnerships, and targeted international cooperation, ensuring that educational modernization aligns with the technological demands of the emerging green economy.

Figure 12 visualizes the systemic barriers to workforce development in the Central Asian countries. The diagram organizes these constraints into three interconnected dimensions-institutional, infrastructural, and technological-showing how their interaction produces cumulative effects on the quality of human capital formation.

On the left side, four key groups of constraints are highlighted:

- Institutional Weaknesses (policy fragmentation, limited governance capacity);
- Infrastructure Gaps (shortage of laboratories and competence centers).
- Technological Lag (slow adoption of digital tools and data platforms).
- Industry-Academia Disconnect (weak cooperation with employers and low engagement of the private sector).

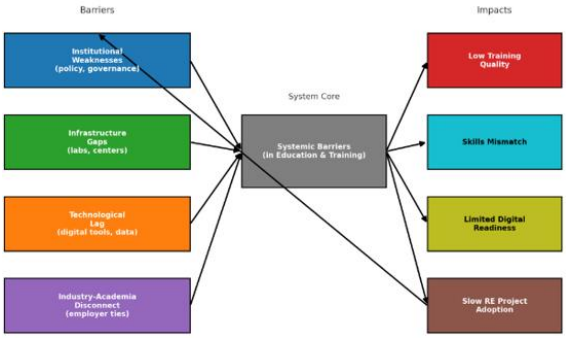


Figure 12: Systemic barriers in workforce development in Central Asia.

These factors converge in the central node, labeled Systemic Barriers in Education and Training, emphasizing their mutually reinforcing nature.

On the right side, the diagram presents the outcomes of these barriers:

- Low Training Quality.
- Skills Mismatch.
- Limited Digital Readiness.
- Slow Renewable Energy (RE) Project Adoption.

A feedback arrow runs from Slow RE Project Adoption back to Institutional Weaknesses, illustrating a negative feedback loop in which the delayed implementation of renewable-energy projects perpetuates institutional inefficiencies and obstructs reform.

Thus, the model demonstrates that solving the human-capital deficit requires simultaneous institutional, infrastructural, and technological transformations, combined with stronger university-industry partnerships and integrated governance mechanisms.

4.4 Practical Significance of the Findings

The results of this study have direct policy relevance for the design of educational and institutional strategies in the Central Asian region. They demonstrate that without modernization of educational infrastructure and deeper integration of the private sector, the region risks remaining on the periphery of the global green-energy transition.

Table 11 outlines the key directions for reform in the system of workforce preparation for the

renewable-energy sector and specifies practical measures for their implementation.

A top priority is curriculum modernization, which should incorporate interdisciplinary modules that integrate energy engineering, environmental management, and digital technologies. This approach will prepare a new generation of specialists capable of addressing the technological and ecological challenges of the energy transition.

Table 11: Potential directions for workforce development reform.

Reform Area	Specific Measures
Curriculum Modernization	Introduction of interdisciplinary modules combining energy, ecology, and digitalization.
Infrastructure Enhancement	Establishment of modern laboratories and competence centers.
Digital Integration	Deployment of simulators, online learning, and IoT-based training platforms.
Business Partnerships	Dual education programs, internships, and corporate training.
International Cooperation	Joint master's programs, exchange schemes, and academic mobility initiatives.

The second direction involves strengthening educational infrastructure through the establishment of modern laboratories and competence centers, enabling practice-oriented learning and experimentation.

The third reform area is digital integration, which includes the deployment of simulators, online learning platforms, and IoT-based systems for remote training and performance monitoring.

The fourth direction, partnership with business, aims to develop dual-education schemes, internships, and corporate retraining programs, bridging the gap between theoretical education and market needs.

Finally, international cooperation should focus on joint degree programs, student and faculty exchanges, and academic mobility, ensuring the transfer of global best practices and international accreditation of regional programs.

Together, these initiatives constitute a comprehensive reform strategy, combining educational, technological, and institutional measures to enhance the region's human-capital competitiveness in the renewable-energy domain.

All aggregated datasets, coding schemes, and regression output tables used in this study are provided as Supplementary Material (Appendix A-C) to enable transparency, reproducibility, and further comparative analysis.

5 CONCLUSIONS

This study, devoted to the development of a qualified workforce in the green-energy sector of Central Asia, has identified both positive dynamics and systemic constraints requiring long-term solutions.

Using a mixed-methods approach-including statistical analysis, comparative benchmarking, expert interviews, and case studies-the research provides a comprehensive assessment of the region's educational and workforce infrastructure, as well as its alignment with international experience.

The findings indicate that while the number of university programs and retraining centers has grown steadily-particularly in Kazakhstan and Uzbekistan-the overall quality of workforce preparation remains low. Only 21% of specialists in the renewable-energy field possess advanced qualifications, compared to 68% in Europe and 65% in North America.

The main barriers include inadequate laboratory infrastructure, weak integration of digital technologies in the learning process, misalignment of curricula with labor-market demands, and limited private-sector involvement in educational initiatives.

The comparative analysis confirms a strong positive correlation between education investment and workforce quality. Central Asia, allocating just 2.1% of GDP to higher education-compared with 4.5-5.0% in Europe and North America-faces structural risks such as skills mismatch, low digital readiness, and slower adoption of renewable-energy projects.

Nevertheless, the study also identifies significant opportunities. The region possesses abundant renewable resources (solar, wind, and hydropower) and growing governmental commitment to green economic policies. To realize this potential, active educational reform is essential. The priority areas include curriculum renewal, infrastructure strengthening, digital transformation, public-private partnerships, and international collaboration.

Ultimately, the primary challenge for Central Asian countries is to shift from quantitative expansion to qualitative enhancement of educational initiatives. Only through comprehensive modernization of the workforce development system can the region close the gap with advanced economies and secure successful integration into the global renewable-energy transition.

The findings affirm that human capital is the pivotal factor of sustainable energy transformation. Without substantial investment in education and training, the transition to a green economy in Central Asia will remain constrained and uneven.

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Sustainable Route Selection Using Fuzzy MCDM Techniques

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Abstract: Effective transportation route assessment is critical to transportation mobility, safety, and sustainability between urban cities. However, selecting the optimal route with consideration of sustainability is still a fresh challenge. This study aims to define the best pathway to utilize, taking into consideration several performance measures such as travel efficiency, safety, impact on the environment, and the quality of infrastructure between Baghdad and Fallujah. The methodology involves three phases, starting with creating an initial decision matrix that compares three assigned road routes with 12 criteria. The weight fuzzy judgment method (WFJM) was used to establish the relative significance of the twelve criteria for the assigned peak periods, considering the differences in the traffic patterns and priorities in the operations throughout the day. The roads were then ranked using the Multi-Objective Optimization by Ratio Analysis plus Full Multiplicative Form (MULTIMOORA) approach, which combines the Ratio System, Reference Point, and Multiplicative Form, followed by a Borda count to get the final ranking. Weighting outcomes suggested that speed limit, road condition, fuel consumption, and pollution were the most important variables during the AM period, whereas during the PM period, lighting and road condition were more significant. The MULTIMOORA findings showed that the Old Abu Ghuraib Route performed better in AM and PM versions and thus had a balanced score across all evaluation systems. The Karmah route and the Expressway No.1 segment had time-varying performance, whereby the Expressway had greater performance in the PM conditions. A sensitivity analysis provided validation of the robustness of the results. This paper provides information to policymakers and motorists on the best driving route selection between Baghdad and Fallujah for management and planning considerations.

1 INTRODUCTION

This study examines the main corridors that connect Baghdad and Fallujah (i.e., the segment of Expressway no. 1, Old Abu Ghuraib Road, and Karmah Road). Generally, the expressway links the main cities of Iraq, including the path from Umm Qasr Port in Basra, Nasiriyah, Al-Diwaniyah, Hillah, Baghdad, Fallujah, and reaching the Jordanian and Syrian borders in Ramadi, allowing both internal and foreign trade. The selected lengths of the Expressway no. 1, Old Abu Ghuraib Road, and Karmah Road are around 71.7, 66.1, 82.0 km, respectively, and the data collection was carried out in 2023. Figure 1 illustrates the selected routes for the study area. The introduction is divided into 6 sub-sections.

1.1 Motivation

Deciding on the best route for road users is one of the crucial aspects of transportation planning, as it directly impacts multiple technical, economic, and practical factors. A bunch of issues faced by road users can arise from traffic congestion, mainly in urban areas, such as stress, delays, and reduced productivity. Thus, to ensure driving with the minimum fuel consumption and the least amount of time, there is a need to develop superior route optimization algorithms that utilize real-time datasets, adaptive routing models, and predictive

analytics [1]. In addition to the fuel prices increasing, environmental concerns make fuel efficiency essential for route selection to avoid and minimize unnecessary acceleration and braking [2].

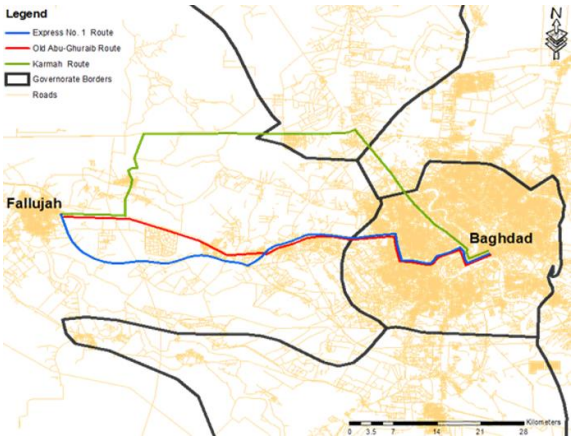


Figure 1: Road corridors connecting Baghdad and Fallujah.

Minimizing fuel consumption means less carbon emissions, which supports environmental preservation and aligns with government policies in addition to sustainable transportation enterprises [3]. Similarly, safety issues are regarded as a major criterion, since accidents can occur due to poor route selection with bad weather conditions, poor visibility, or due to the behavior of drivers [4]. Due to the varied drivers' preferences, some drivers select the shortest route while others prefer fascinating roads or highways for convenience [5]. Furthermore, efficient route optimization is crucial for businesses related to transportation, like ride-sharing, emergency services, and logistics [6], [7]. The traditional route selection models are primarily based on shortest path algorithms like A* Algorithm or Dijkstra's Algorithm. Hence, these traditional models do not constantly take into consideration factors like weather conditions, fuel consumption, road risks, and other cost factors. Due to these challenges, better route selection plays a crucial role in improving people's daily activities and supporting business benefits.

1.2 Problem Statement and Challenges

The decision-making issue of choosing the best transportation path between two cities is a complicated one because it includes the existence of several alternative paths and a broad variety of criteria that impact the final decision [8]. These requirements usually involve commuting time, safety, comfort, environmental effects, and dependability, among others. Not all criteria are of equal importance, and depending on the views of the decision-makers or the stakeholders, or their goals or limitations, they will place various weights on each criterion [9]. In addition, uncertainty as well as vagueness in the evaluation of criteria characterize the decision-making environment, making the process more difficult [10] , [11]. A primary concern is the reliability and availability of the dataset. Consistent and real-time datasets are crucial for Multi-Criteria Decision Making (MCDM) models' operation. Hence, such datasets are not consistently available across different spatial locations and transportation systems. Such complexity cannot be resolved using traditional single-criterion or intuitive methods because they cannot be used to effectively represent conflicting priorities, and they cannot be used to discover inconsistent and uncertain evaluations [12]. Therefore, a systematic and robust methodology that can combine various criteria, as they have different significance, and address the uncertainty, is urgently required to choose the most appropriate path between cities.

The key challenge is to identify and apply the MCDM method that models the complexity of transportation route choice accordingly. Although there are a number of methods of MCDM, they vary in their ability to address inconsistent judgments, uncertainty, and unequal weights of criteria [13]. The challenge is in selecting the method that will guarantee objectivity in the criteria weighting, create a reliable ranking of the alternatives, and make the decision-making process transparent [14]. The ability to balance between theoretical strength and practical application is a primary issue that should be resolved to help decision-makers come up with an optimal and evidence-based solution to the route selection.

1.3 Research Gap and Contribution

Despite the extensive use of MCDM methods in transportation planning [15], [16], the integration of further weighting and ranking approaches towards route evaluation has an obvious theoretical gap. In particular, though the weight fuzzy judgment method (WFJM) has proven to be very beneficial in dealing with inconsistency and uncertainty in decision-making processes [14], little has been done in the application of the method as a weighting mechanism in the transport sector. Likewise, even though such ranking techniques as Ratio Analysis plus Full Multiplicative Form (MULTIMOORA) have become popular due to their high strength and the capacity to provide consistent outcomes in a variety of perspectives, little has been done in the literature that

would imply the integration of WFJM and MULTIMOORA into a single framework of evaluating transportation routes. A bunch of researchers have used MCDM methods. Nevertheless, there are still some gaps in using MCDM for selecting the best driving route. Also, both the evaluation and selection of the best route are still exhibiting some shortcomings, which need to be addressed comprehensively. For instance, when dealing with issues requiring well-structured and similar judgments, Analytic Hierarchy Process (AHP) excels due to its simplicity and hierarchical framework [17]. Nevertheless, since it depends on pairwise comparisons, its subjectivity could lead to mistakes and discrepancies, when the number of criteria increases.

In addition, previous studies have ignored real-time weather, traffic accidents, road closures, and traffic conditions [18]. By using traditional models, some researchers have oversimplified driver preferences by assuming equal values of distance and time for all drivers [19]. On the other hand, some modelers have failed to sufficiently integrate multiple conflicting criteria, when these models struggle to balance factors such as fuel consumption versus travel time or safety versus speed. Furthermore, few researchers have involved real users in validating the serviceability and efficiency of the projected models [20]. Last but not least, the appropriate scaling of large and complex road networks is crucial for route optimization, but it has been missed by some researchers [21], [22]. In order to address the gaps that have been mentioned previously, this research aims to integrate new strategies by making significant contributions:

1) For the first time, the current study used the WFJM model in the field of transportation.
2) The new formative decision matrix contains 12 criteria and 3 alternatives.
3) Integrating global sustainability goals by proposing MCDM systems that account for environmental impacts, such as fuel consumption and emissions.

1.4 Objectives

In order to align the route optimization methodology with the United Nations Sustainable Development Goals, the main objectives are (1) present a precise and reliable weight for 12 criteria and reduce the uncertainty. (2) Minimizing fuel consumption by choosing smoother routes reduces unnecessary stops and congestion, thereby lowering fuel costs and vehicle emissions. (3) The study also focuses on minimizing travel time by identifying the best route that allows drivers to reach their destination in the shortest travel time to achieve time savings, improve productivity, and reduce driver fatigue. (4) Besides, verifying the optimum driving route selection approach is crucial to utilize real-world datasets to determine the driver preferences and validate its practical feasibility.

1.5 Significance of the Study

The significance of research is to contribute to the enhancement of the decision-making process in transportation planning by combining the application of the WFJM and the MULTIMOORA. The integrated application of WFJM and MULTIMOORA would enable the decision-makers to attain uniformity and certainty in ranking the transportation routes, as well as to respond to the uncertainty and variability of the expert opinion. The integration of this method also adds to the literature, where these methods can help resolve the divide between theoretical rigor and applications. Practically, the paper provides a decision support instrument to the transportation authorities, urban planners, and policymakers to choose the best routes that can provide maximum efficiency, reduce their environmental impacts, and support the general societal interests. Moreover, considering the growing need to develop sustainable transportation systems globally, the methodology used in this work demonstrates how the crisis can be addressed with the help of scientific methods of decision-making to make the transport infrastructure more sustainable and resilient. In addition to the particular context of the three transport routes considered, there is the importance of delivering a framework that is reproducible and can be applied to other geographic areas, modes of transport, or infrastructure endeavors, where decisions made are not only evidence-based but also consistent with long-term development plans. Finally, this work showcases the power of our techniques, not only in providing the best possible route but also in building stakeholder trust, transparency and accountability in the decision-making processes of large-scale infrastructure projects.

1.6 Literature Review

A bunch of interrelated factors influence the complex task of driving route selection, such as distance, traffic congestion, fuel consumption, safety considerations, travel time, and environmental

impact. Consequently, in order to balance multiple criteria based on both system objectives and driver preferences, MCDM, one of the AI applications, has been used as a valuable framework [23], [24]. By considering both qualitative and quantitative criteria, MCDM sustains multiple processes of context-aware and informed decision making. Multiple studies have inspected the relevance of MCDM in transportation, especially in relation to the personalization and compliance of driver route choice systems [25]. In addition, the integration of MCDM with real-time traffic data alongside emerging technologies such as machine learning has surged its applicability in user-centric development and smart navigation systems [26].

MCDM includes a wide range of organized approaches intended for multiple conflicting purposes that should be simultaneously considered. For instance, one of the widely used techniques, AHP, simplifies decision complexity by using a hierarchical structure of both criteria and sub-criteria to determine relative importance over pairwise comparisons [27]. Another commonly used model, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), allows the distinguishing between different alternative paths by ranking alternatives according to their geometric distance from anti-ideal and hypothetical resolution [28]. To categorize the alternatives that are employed to offer the optimal compromise among different requirements in a multi-dimensional space, the VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) model has also been utilized to emphasize compromise solutions [29]. Also, to compare multiple alternatives, ELimination and Choice Expressing REality (ELECTRE) models are another type of MCDM that uses ranking relationships, particularly in cases involving difficult-to-quantify preferences. Besides, fuzzy MCDM models incorporate fuzzy logic to account for both bias and ambiguity factors in real-world scenarios of transportation, like drivers' safety considerations and comfort [30]. The previously mentioned techniques are widely utilized in selecting the best driving route. Hence, decision-makers should take into consideration both qualitative and quantitative factors, which reflect the appropriate priorities and needs of road users [31]. For instance, Ekhlakov and Andriyanov [32] applied a MCDM approach by utilizing the AHP and TOPSIS for selecting the optimum driving route. Criteria such as distance, travel time, road traffic, safety, road type, road surface quality, travel cost, and weather conditions were included for modelling. Other criteria like selecting the shortest time, fastest speed, and safest conditions were selected to optimize the optimum driving routes by using MCDM methods such as AHP, Fuzzy AHP, TOPSIS, and Fuzzy TOPSIS [33]. Nevertheless, for the same purpose, Vrtagić et al., [34] utilized another type of criteria such as segemnt length, slope of road, speed limit, and accidents. Moreover, other bunch of researchers preferred to select criteria such as travel time, risk level, and travel cost combined with MCDM models such as AHP, Data Envelopment Analysis (DEA), TOPSIS for route optimization [35].

In order to address both qualitative and quantitative decision factors in route selection improvement across complex transportation networks, there is a crucial need for an integrated framework. For instance, Koohathongsumrit and Meethom [36] presented a hybrid MCDM model that integrates the TOPSIS, AHP, and DEA for problem addressing based on qualitative and qualitative criteria. Other researchers, such as Hassannayebi et al. [37], applied the ELECTRE and Condorcet models to estimate bus service reliability utilizing multiple performance indicators. This research highlights the usefulness of fuzzy logic in managing the essential imprecision and uncertainty of transportation datasets. Another type of MCDM models demonstrates the use of weighting systems, both objective and subjective, to enhance route selection under diverse network conditions. For instance, Nie et al. [38] combined Multi-Attribute Decision Making with heuristic path search to enhance vehicular safety messaging. Moreover, Huang et al. [5] demonstrated an approach to adaptive route endorsement. This model uses a historical navigation dataset for user conducting modelling by employing a Deep-Cross-Recurrent learning model, which integrates both LSTM and DCN-v2 styles.

On the other hand, fuzzy MCDM techniques stand out due to their capability to cope with imprecise input data and linguistic variables [39] . This is particularly useful for modeling consumer preferences, levels of comfort, or safety perceptions, which are often difficult to quantify using accurate quantitative measures. Fuzzy logic techniques enhance the accuracy and adaptability of decision models, allowing them to more accurately represent the real-world complexity [40]. While the ability to capture the fluctuation and unpredictability of the driving route selection based on human participation, both hybrid MCDM and fuzzy techniques are increasingly becoming the preferred approaches in transportation planning [41].

Recent studies of traffic planning have facilitated the integration of MCDM models with factors that directly impact drivers' route selection. Beyond basic geographic considerations, optimal route selection using MCDM models should encompass dynamic variables like emission levels, fuel consumption, traffic volumes, accident rates, and vehicle speeds. These criteria enhance drivers' awareness and support alternative driving route selection [42]. For instance, algorithm weights can be adjusted by assigning more weight to safety (i.e., high-risk zones) than economy (i.e., fuel consumption) depending on circumstances or user preferences. In addition, decision quality can be improved by integrating various criteria into MCDM preferences, especially under rapid and uncertain fluctuating traffic scenarios. By developing the optimality of the route and aligning with broader objectives, this study offers a robust foundation for transportation planning and superior navigation [43].

Unlike prior studies that have approached MCDM with limited criteria, this research presents a WFJM and MULTIMOORA models with 12 criteria, like travel time, accidents, and geometric design of routes in addition to other criteria that highly impact the mood of drivers for route selection.

2 METHODOLOGY

This study suggests an organized three-phase methodology to address complicated decision-making scenarios, including multiple and occasionally conflicting criteria. The first phase develops the judgment/decision matrix along with the assessment criteria, guaranteeing the appropriate illustration of both quantitative and qualitative factors. Assessment of the expert and theoretical basis for process fulfillment is regarded as assembly integration. The second phase applies the WFJM to estimate the relative importance of criteria. By integrating expert input with fuzzy set theory, WFJM efficiently addresses bias and vagueness, converting ambiguous judgements into reliable numerical values. The last phase of methodology consists of applying the technique of MULTIMOORA, an improved version of Multi-Objective Optimization by Ratio Analysis (MOORA) that integrates the ratio system, reference point, and entire exponential procedures into a single robust framework. Besides, MULTIMOORA utilizes WFJM-derived weights for thorough ranking of alternatives, reducing bias and improving decision reliability. To provide an unambiguous, rigorous, and responsive decision-making procedure suitable for intricate estimation scenarios in unpredictable situations, the combination of these steps is crucial to implement.

2.1 Decision Matrix

The established judgement/decision matrix for this research acts as a fundamental structure for organizing the methodological and assessing the multiple selected routes for the investigation aspect. It comprises two primary components, judgment criteria and alternatives. Each of these components performs a distinct yet complementary purpose throughout the process of decision-making. The alternatives demonstrate the main segments of selected roads for comparison facets. Three essential segments of roads were selected for this research, each with particular topographical, functional, and structural characteristics. An essential freeway through the regional roads network, the first, a selected road segment of Expressway No. 1, is characterized by high mobility and strict access control. The second route option, named locally as Old Abu Ghuraib Road, acts as a crucial urban road and is mainly utilized by road users to drive between Baghdad and Fallujah. The third option is the Karmah Road, a major local route that links multiple neighborhoods by combining both urban and rural elements of transportation.

The second component of the assigned criteria indicates an array of characteristics or performance indicators against which each option is assessed. During the MCDM analysis, there are two crucial terms that should have been taken into consideration through analysis: cost (C) and benefit (B). The cost illustrates the criteria when lower values are desired, indicating cost, effort, or adverse effects that should be minimized through the decision-making process. In contrast, benefit depicts any criteria when higher values are desired, signifying benefits, advantages, or even positive effects that ought to be maximized over the process of decision-making. The designated criteria were selected due to their rank in terms of traffic performance, overall safety, environmental sustainability, and infrastructure resilience. These criteria were established based on a dataset comprising real field measurements, traffic and accident records, professional road inspections, and environmental surveillance data. The assigned criteria consist of the length of each selected road segment and travel time, defined as the average time required to traverse a selected road segment under specific conditions. Density is also one of these criteria, which illustrates the number of vehicles within an assigned length of the road. The speed limit

is also a crucial criterion when it is the maximum allowable speed that can be used by road users [44]. The rate of accidents is defined as the number of accidents per unit of time along a specified segment of the road [45]. The number of lanes and road surface conditions are also involved within the selected criteria at this study.

It is worth mentioning that the calculated criteria were collected during both selected peak AM (i.e., from 8:00 to 9:00 am) and PM (i.e., from 4:00 to 5:00 pm) periods. Each of these criteria was selected to reflect an imperative aspect of road performance, ensuring that the evaluation considered not only the efficiency of the trip, but also some factors such as safety, operational conditions, and environmental effect. By combining these multiple features into one neatly arranged decision matrix, this study presents a robust and unambiguous framework for elegant procedures of multicriteria decision making. This structure enables an organized assessment of different alternatives, besides improving the interpretation and consistency of analysis. These aspects are essential for establishing policies, infrastructure investment decisions, and further academic research on transportation system assessment.

The vital dataset utilized as criteria in this research consists of a bunch of key metrics. For instance, the reported number of accidents to law enforcement during a certain time period, by the length of the assigned road segment and the average speed of vehicles, was calculated by the floating car method. The selected data collection techniques guarantee accurate estimation, support successful transportation planning, and enable robust decision making.

Traffic density was performed manually by recording camera footage, when the observers review the recordings for vehicle counting passing through an assigned road segment during a specified time frame [46]. Consequently, traffic density was computed by dividing the number of observed vehicles by the length of the road segment. The determination of road condition was performed through site inspection, which offered an extensive estimation of pavement physical quality and related infrastructure.

Monitoring some factors, such as the existence of potholes, cracks, rutting, drainage efficiency, surface roughness, and shoulder conditions, was also performed within the inspection. The visual observations were frequently enhanced with defined assessment scales or indications of condition to recognize the extent and severity of deterioration [47].

The calculation of fuel consumption during peak hours was estimated by multiplying peak traffic volume, road segment length, and the number of peak traffic hours, then dividing by the assumed average fuel consumption efficiency factor for each vehicle (i.e., 10 km/l) [48]. The levels of pollution were estimated by using the road segment length, peak hours duration, and traffic volumes during peak hours. The latter values were multiplied by the CO_2 emission factor (i.e., 2.3 kg/l) and divided all by the average fuel efficiency of 10 km/l [49]. The resulting computation provides an estimate of the entire quantity of pollution that was generated during peak hours. This assists in understanding how traffic conditions impact the environment. Moreover, inspection surveys were conducted to identify all the remaining criteria, such as the existence of jersey barriers, the number of lanes, the presence of security checkpoints, and road lighting.

2.2 WFJM Method

The WFJM approach is principally divided into five stages. The first stage is like other MCDM models, in which the input consists of different sets of m alternatives (i.e., A1, A2, …, Am) along with n preferences of criteria (C1, C2, …, Cn). The intersection of criteria and alternatives is characterized as a decision matrix. Besides, the second stage, standardization, comprises utilizing the knowledge of experts to classify criteria as either cost or benefit types. The next step applies a normalization formula to the assigned values [50].

$$c_{ij} = \frac{c_{ij} - \min_i x_{ij}}{\max_i x_{ij} - \min_i x_{ij}} \text{ ; for benefit criterion} \quad (1)$$

$$c_{ij} = \frac{\max_i x_{ij} - c_{ij}}{\max_i x_{ij} - \min_i x_{ij}} \text{; for cost criterion} \quad (2)$$

The third stage comprises two steps: both expert identification and evaluation. The first step consists of selecting and recognizing professionals who have earned the confidence of their peers. In order to confirm availability and interest, selected experts were contacted via official email. The expert review and the development of an assessment form is regarded as the second step involved. In addition, this step comprises establishing an estimation form to gather expert input while ensuring its reliability and validity, which are of paramount importance.

The data transformation, the fourth stage, encompasses two steps. The first step involves identifying optimum values. There are three different classes of optimum values, regarded as the most feasible responses to this obligation. In some cases, the first group corresponds to higher values. For

instance, considering the grades of students, higher values correspond to better performance. In contrast, in the second case, the smallest value is the optimal. For instance, in network security concerns, smaller values are preferable. At the very least, some cases consist of optimum values that fall approximately in the middle range, like blood pressure. Hence, the recommended approach is crucial for addressing issues associated with varying weights in MCDM models. (3) illustrates the ideal solution.

$$A^{*} = \{((\max_i x_{ij} | x \in X) \cdot (\min_i x_{ij} | x \in X) \cdot (J_{ij} \in I.J) \mid i = 1.2.3 \ldots . m)\}. \quad (3)$$

In this context, max denotes the best optimum feasible value based on the advantageous criteria, while min illustrates the best potential value based on non-benefit criteria, and j_{ij} identify the critical quantity. Ideally, the optimal value lies within the range between the most extreme and the least extreme values. The subsequent stage entails comparing the best selected options against other alternatives. The outcome is a comparison of the best potential outcome for each criterion with other alternatives for the same criterion. In order to determine the alternative's deviation from the ideal alternative, weights are applied to reflect relative importance. Five linguistic metrics were utilized for comparison: big difference, huge difference, slight difference, and no difference. (4) depicts the mentioned process.

$$Op_{Lang} = \left\{\left(\begin{pmatrix}\tilde{x} \\ ij\end{pmatrix} \otimes x_{ij} \mid j \in J\right).\middle| \, i = 1.2.3 \ldots . m\right\} \quad (4)$$

In order to determine the best response and compare it to the other alternatives, $\otimes$ utilizes as the standard for comparison. The main theoretical basis for developing the assessment matrix is a comparison between the optimum and the alternative values under the same circumstances. Moreover, due to the development on the assessment matrix and evaluation within each criterion separately, the proposed system at this research has no inaccuracy.

Finally, the fifth stage involves employing the fuzzy function of membership. To improve the judgment matrix, the function of fuzzy membership is applied, followed by a defuzzification procedure. In order to ensure a logical procedure, these processes develop the practical precision and applicability of dataset usage. Nevertheless, imprecision and uncertainty may arise due to the challenges related to assigning weights to each criterion in MCDM models. Al-Hchaimi et. al [51] specified that utilizing fuzzy values instead of precise values enables better measurement of criterion significance, especially when addressing issues of fuzziness and ambiguity. Allowing decision-makers to express their viewpoint using linguistic variables is regarded as one of the benefits.

of Fuzzy Cognitive Systems (FCSs), especially when it enhances awareness and flexibility of experts. Moreover, for more realistic assessments of evaluated information, FCSs employ a boarder set of discrete points to present fuzziness and ambiguity in indeterminate concepts [52]. The theory of the fuzzy cloud can be defined using multiple classifications. The first definition, K is assumed as a qualitative concept belonging to a space Q. $x \in Q$ is regarded as a random recognition of K, satisfying $x \sim N$ (Ex, En2), and $En' \sim N$ (En, He2). $\mu T(x) \in [0, 1]$ is the convinced degree of x on K, which can be illustrated in equation (5):

$$\mu_K(x) = \exp\left(-\frac{(x - Ex)^2}{2(En')^2}\right) \quad (5)$$

The second definition states that D_1 = (Ex1, En1, He1) and $D_2 = (Ex_2, En_2, He_2)$ as a random cloud, while the value of λ is regarded as an actual value. The following outlines the principle of arithmetic operations, which can be illustrated as follows.

$$D_1 \pm D_2 = \left(Ex_1 \pm Ex_2, \sqrt{En_1^2 + En_2^2}, \sqrt{He_1^2 + He_2^2}\right) \quad (6)$$

$$D_1 \times D_2 = \left(Ex_1 Ex_2, |Ex_1 Ex_2| \times \sqrt{\left(\frac{En_1}{Ex_1}\right)^2 + \left(\frac{En_2}{Ex_2}\right)^2}, |Ex_1 Ex_2| \times \sqrt{\left(\frac{He_1}{Ex_1}\right)^2 + \left(\frac{He_2}{Ex_2}\right)^2}\right) \quad (7)$$

$$\frac{D_1}{D_2} = \left(\frac{Ex_1}{Ex_2}, \left|\frac{Ex_1}{Ex_2}\right| \times \sqrt{\left(\frac{En_1}{Ex_1}\right)^2 + \left(\frac{En_2}{Ex_2}\right)^2}, \left|\frac{Ex_1}{Ex_2}\right| \times \sqrt{\left(\frac{He_1}{Ex_1}\right)^2 + \left(\frac{He_2}{Ex_2}\right)^2}\right). \quad (8)$$

Table 1 illustrates the linguistic terms using FCS. In order to reach the optimum values for the estimation criteria (w_1, w_2, …, w_n) T of coefficient weights, the following steps are applied.

1) By combining equation 6 with the formally applied FCS formula, the fuzzification ratio dataset is determined, which can be denoted as A. For instance, the first criterion in the fuzzy representation can be illustrated as A_{C1}, and the second criterion is A_{C2}, which can be applied to the remaining criteria.
2) By applying the same procedure for all criteria, the summary of $\{A_{C1}, A_{C1}, A_{C1}\}/3$ can be utilized.
3) The obtained outcome of the above second step can be standardized by dividing it by the summation of the related results of the same

step, thereby providing the final criterion weight. Nevertheless, the weight should equal 1.0, as demonstrated in (9).

$$W = \frac{\left(\sum_{i=1}^{m} \frac{\left(\overline{(A_{cj})}\right)}{\left(\sum_{j=1}^{n} (A_{cj})\right)} \right)}{m} \quad \text{, for i} = 1,2,3, \ldots \text{m and j} = 1,2, \ldots \text{n.} \tag{9}$$

Table 1: Linguistic terms.

Linguistic terms	Nume-rical	Cloud value		
No_Difference (ND)	1	0.000	0.673	0.101
Slight_Difference (SD)	2	3.0988	0.453	0.068
Difference (D)	3	5.000	0.278	0.041
Big_Difference (BD)	4	8.262	0.579	0.086
Huge_Difference (HD)	5	10	0.673	0.101

2.3 MULTIMOORA Method

Through the analysis of ratios, a bunch of researchers have approached the optimization of the multi-objective optimization method (MOORA) [53]. In order to enhance its robustness, researchers extended this method by integrating a full multiplicative model with MOORA, known as MULTIMOORA [54]. This method has been applied in multiple domains of study, such as provincial assessments, cross-national evaluations, and investment management [55]. The MOORA method initiates with matrix X, where each entry x_ij indicates ith alternative associated with jth purpose (i = 1, 2,..,m; j = 1, 2..,,n). It involves two components: the ratio approach and the basis point approach. Brauers et al. [56] stated that the weighting methodology comprises two steps, depending on the relevance of outcomes. A bunch of other researchers have addressed the issue of normalization [57]. Moreover, other researchers have examined the issue of weighting [58]. The MULTIMOORA model focuses on internal standardization and treats all objectives equally. For instance, stakeholders associated with the topic might give a preference to a particular purpose. Hence, in order to depict a response on a target, either multiplying the dimensionless number, which reflects the response of the objective by an impact coefficient, or dividing the objective into multiple sub-objectives [59]. By comparing different options of objectives to different potential outcomes, MOORA's ratio system adjusts the dataset as illustrated in (10).

$$x_{ij}^{*} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^{2}}}, \tag{10}$$

X_{ij} Represents the ith alternative for the Jth objective. In general, these values range between 0 and 1. In addition, criteria may be included or excluded based on their optimal value (i.e., minimum or maximum).

The considered index for every selection is calculated by (11).

$$y_{i}^{*} = \sum_{j=1}^{g} x_{ij}^{*} - \sum_{j=g+1}^{n} x_{ij}^{*} \tag{11}$$

It is worth mentioning that g signifies the number of objectives that should be maximized. At this stage, each ratio is assigned a rank, where a higher index corresponds to a higher rank.

The reference point approach in the MOORA is directly related to the ratio system. According to the specified ratios, (11) is utilized to determine the Maximal Objective Reference Point vector. The Jth coordinate of the reference point is expressed as rj = max(ix) in the optimization context. Each coordinate of this vector specifies the minimum or maximum value of a specific objective. Subsequently, each component of the normalized response matrix is calibrated accordingly. In addition, the final ranking is determined according to the deviation between the reference point and the minimum and/or maximum Metric as illustrated in (12).

$$\min_{i} \left(\max_{j} \left| r_{j} - x_{ij}^{*} \right| \right). \tag{12}$$

Updating the MOORA method was enhanced by Kreinovich and Cheu [60] through the integration of a full Multiplication Form methodology. This method consists of both optimizing and reducing the sole exponential utility function. The dimensionless quantity is regarded as the practical utility of the ith alternative, as illustrated in (13).

$$U_{i}' = \frac{A_{i}}{B_{i}}. \tag{13}$$

According to (13), A_i is defined as Πig=1 xij; i = 1; 2 where m represents the invention of the purposes that belong to the ith alternative to be maximized with g = 1, …, n. Also, Bi = Πig=1 X_{ij} Illustrates the objective product of the ith that is minimized with n

– g, the number of indications that should be minimized. It is crucial to mention that the MULTIMOORA includes both the full multiplicative form and MOORA components (Ratio Systems and Reference Points) [61].

3 RESULTS AND DISCUSSION

3.1 Results

According to the methodological approach described in the previous section, the analysis of the three main routes between Baghdad and Fallujah was conducted through a series of analytical stages. The results obtained for the selected road segments are presented below.

At the first stage, a decision matrix was constructed based on the selected evaluation criteria. This step was performed separately for the AM and PM peak periods to capture temporal variations in traffic conditions. The decision matrix is presented in Table A1 (Appendix) and serves as the basis for subsequent weighting and ranking procedures.

The weighting process was carried out using the WFJM method to determine the normalized importance of each criterion for both time periods (Figure 2). The results indicate that during the AM period, the most influential factors are speed limit (0.14245), road condition (0.11506), fuel consumption (0.11506), and pollution (0.11506), highlighting the importance of operational efficiency and environmental impact. Safety-related factors, such as accident frequency (0.07293) and road density (0.08748), also play a significant role due to congestion during morning hours. In contrast, factors such as checkpoints (0.03460) and jersey barriers (0.05830) have a lower impact.

In the PM period, the importance of lighting (0.17495) and road condition (0.11749) increases, reflecting greater concern for visibility and safety. While speed limit remains significant (0.11749), other factors such as road density, pollution, and fuel consumption show moderate influence. The increased weight of jersey barriers (0.08933) indicates higher safety requirements during evening travel. Overall, morning conditions emphasize efficiency, whereas evening conditions prioritize safety and visibility.

The ranking of alternatives was performed using the MULTIMOORA method. The evaluation combines three approaches—Ratio System, Reference Point, and Multiplicative Form—and aggregates the results using the Borda count (Table 2), ensuring a comprehensive and balanced decision-making process.

For the AM period, the Old Abu Ghuraib Route achieves the highest overall ranking with a Borda score of 8.0, despite not being the top performer in each individual method. This indicates consistent performance across all evaluation approaches. The Expressway Route and Karmah Route share the second position with equal scores.

In the PM period, the Old Abu Ghuraib Route maintains its leading position, confirming its stability across different time conditions. The Expressway Route ranks second, likely due to improved evening conditions such as lighting and traffic flow, while the Karmah Route ranks third due to less favorable conditions. Overall, the results demonstrate that the Old Abu Ghuraib Route is the most reliable and balanced option.

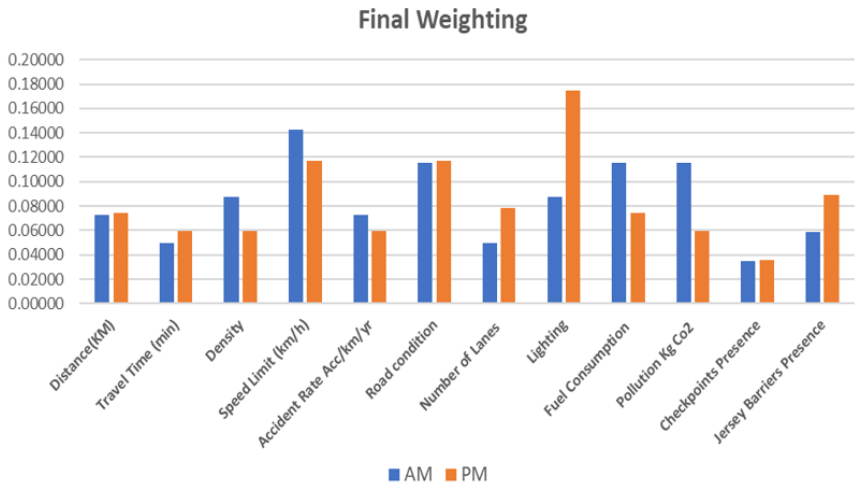


Figure 2: Final weight.

Table 2: Final rank.

Period	Path route	Ratio System	Reference Point	Multiplicative Form	Borda Score	Final Rank
AM	Expressway Route	1	3	1	5	2
	Old Abu Ghuraib Route	3	2	3	8	1
	Karmah Route	2	1	2	5	2
PM	Expressway Route	2	3	1	6	2
	Old Abu Ghuraib Route	3	2	3	8	1
	Karmah Route	1	2	2	5	3

3.2 Validation and Sensitivity Analysis

To verify the robustness and reliability of the obtained results, a sensitivity analysis was conducted (Figure 3). In this process, the weights of the evaluation criteria were systematically varied within a reasonable range, and the impact of these variations on the final ranking was examined.

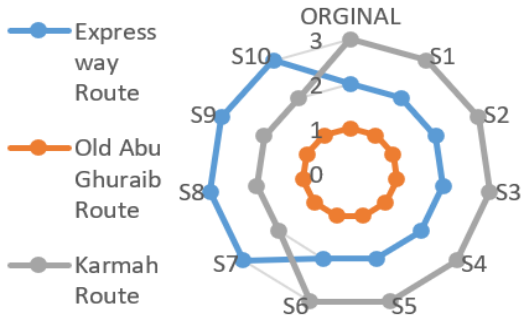


Figure 3: Sensitivity analysis.

The results show that the Old Abu Ghuraib Route consistently maintains the first position under both AM and PM conditions, even with significant changes in criteria weights. This stability indicates that the final decision is not overly sensitive to specific weighting schemes and confirms the robustness of the model.

Although minor ranking variations were observed for the Expressway and Karmah routes, these changes did not affect the overall ranking outcome. Therefore, the results obtained using the MULTIMOORA method can be considered reliable and consistent for decision-making purposes.

4 CONCLUSIONS

To utilize both the criterion dataset and expert judgement, a selected segment of Expressway No.1, the Old Abu Ghuraib Road, and the Karmah Road, regarded as the main social and economic arteries of road users between Baghdad and Fallujah, was subjected to thorough analysis in this study. Three methodological phases were taken into consideration for the complicated performance evaluation of the three selected routes (i.e., identification of the full set of criteria, assessing the significance of criteria by WFJM, and ranking the alternatives using MULTIMOORA approach.

Through three-phase integration, this study identified the route that operates best when the methodology is applied thoroughly and spatially accurately. Both AM and PM analyses of WFJM revealed temporal variations in the significance of the inspection criterion. For instance, during the AM period, environmental and operational factors like road condition, fuel consumption, speed limit, and pollution, combined with safety-related factors like accident frequency and traffic density, were the most significant. Conversely, the PM period emphasized visibility, safety, lighting, road condition, and the presence of jersey barriers as the most of significant criteria. Nevertheless, both environmental and traffic flow factors had an insignificant impact.

Based on MULTIMOORA analysis (i.e., ratio system, method of reference point, and Borda count aggregation for multiplicative form), the Old Abu Ghuraib Road was recognized as the ideal and the most reliable option for road users during both AM and PM circumstances. However, depending on the evaluation method and time period, both segments of Expressway No. 1 and the Karmah Road performed moderately but inconsistently. By confirming both stability and robustness of the final decision, the sensitivity analysis depicted that the Old Abu Ghuraib Road maintained its top ranking under different weighting conditions. Though all three selected routes are crucial for the regional transportation network, the Old Abu Ghuraib Road still performs best in terms of safety, operational efficiency, environmental impact, and infrastructural quality, despite temporal traffic variations.

Like others in the literature, this study has limitations. This paper studies only three selected routes that were evaluated based on the available data

and assessment criteria. However, a high percentage of drivers between Baghdad and Fallujah utilize these three selected routes. In addition to the traditional MCDM frameworks, such as Weighted Product Method (WPM), AHP, and Analytic Network Process (ANP), could have been employed, but the selected method offers specific advantages when it processes the inconsistency, one of the main gaps over the MCDM methods. For future studies, the research recommends adding another fuzzy with the methods used in this research. Also, incorporating criteria such as seasonal variations, environmental data, and broader socioeconomic effects into the MCDM framework could further route optimization. Moreover, integrating multi-model transportation systems and last-mile interactions would offer a much thorough perspective on urban mobility.

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APPENDIX

Table A1 presents the decision matrix used in this study, summarizing the performance values of all three route alternatives across the selected criteria for both AM and PM peak periods. The matrix serves as the primary input for the WFJM weighting process and subsequent MULTIMOORA ranking analysis, ensuring a consistent and structured evaluation of route performance under varying traffic conditions.

Table A1: Decision matrix.

Criteria		AM		
		Expressway Route	Old Abu Ghuraib Route	Karmah Route
Traffic and performance	Distance (KM) (C)	71.7	66.1	82
	Travel Time (min) (C)	81	81	82
	Density (C)	High	Medium	Low
	Speed Limit (km/h) (B)	120	100	60
	Accident Rate (C) Acc/km/yr	0.89	0.83	0.28
Road Quality & Infrastructure	Road condition	Excellent	Good	Fair
	Number of Lanes (B)	3	3	1
	Lighting	Yes	No	No
Cost Considerations	Fuel Consumption (C) Liter	70389	15153	10557
Environmental impact	Pollution (C) Kg Co2	161895	34852	24281.1
Safety Features	Checkpoints Presence	Yes	No	No
	Jersey Barriers Presence	Yes	No	No
Criteria		PM		
		Expressway Route	Old Abu Ghuraib Route	Karmah Route
Traffic and performance	Distance(KM) (C)	71.7	66.1	82
	Travel Time (min) (C)	87	72	93
	Density (C)	High	Medium	Low
	Speed Limit (km/h) (B)	120	100	60
	Accident Rate (C) Acc/km/yr	0.89	0.83	0.28
Road Quality & Infrastructure	Road condition	excellent	Good	Fair
	Number of Lanes (B)	3	3	1
	Lighting	Yes	No	No
Cost Considerations	Fuel Consumption (C) Liter	111947	14492	10106
Environmental impact	Pollution (C) Kg Co2	257478	33332	23244
Safety Features	Checkpoints Presence	Yes	No	No
	Jersey Barriers Presence	Yes	No	No

Ethical Risks and Improvement Potentials of AI Tools in Carbon Footprint Calculation: The Case of XAI

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Keywords: AI Ethics, Carbon Footprint Calculation, Explainability, Transparency, Explainable AI (XAI), Sustainable Development.

Abstract: This study aims to explore the ethical risks from AI tools in carbon footprint calculation applications, especially focusing on Explainability and Transparency. Although AI provides convenient computing, the problem of "black box" may lead to a variety of ethical concerns caused by computing. This study first systematically reviews multiple documents and analyses to understand the initiatives for AI ethics and the risks arising from unexplainability and opacity. This study proposes Explainable Artificial Intelligence (XAI) as a solution to mitigate these ethical risks. The paper further explores how XAI can improve the transparency of carbon footprint calculation and its specific implementation by users through simulation of real-world scenarios. The Results show that XAI technology can transform AI's abstract predictions into mathematically rigorous and actionable evidence, enabling users to implement specific carbon reduction behaviours in their lives. Ultimately, this research contributes to the growing discourse on responsible AI by demonstrating how explainable models can foster trust, accountability, and sustainability in data-driven environmental decision-making.

1 INTRODUCTION

When we discuss the SDGs (Sustainable Development Goals) and ESG (Environmental, Social, and Governance), calculating carbon footprints is a crucial topic. For example, the ISO 1404X family of standards establishes a rigorous and comprehensive methodology, providing appropriate methods for different areas and yielding meaningful results. At the same time, many online carbon footprint calculators that provide personal carbon footprint calculations are used as calculation tools, and Generative AI (Hereinafter referred to as AI) can also be used to calculate the carbon footprint of personal life or organizations. AI technology has the potential to develop rapidly and be highly applicable in the field of sustainable development, especially in terms of carbon footprint calculation and optimization. As a convenient auxiliary tool, AI can provide a lot of important information and help users avoid complex calculations to obtain concise results.

While AI's efficiency comes with risks, we accept its output, but are AI's calculations biased? Are the results transparent within the AI's black box? Do the results adhere to the principles of sustainability and fairness? These issues, combined with human biases toward sustainability or green energy, can lead to biased judgments about the output. For example, Holmgren et al. conducted an experiment and found that people tend to incorporate compensatory green beliefs into less environmentally friendly objects, thereby lowering the calculated GHG CO2e values [1]. This reduced footprint may be due to averaging bias. Furthermore, regarding carbon footprint calculators, Murlow et al. noted in their research that these calculators vary greatly in details and boundaries and are often poorly designed to suit users. These AI operations can be subject to human error, leading to erroneous data output [2].

Based on questions above, this study aims to examine the ethical risks inherent in AI tools used in carbon footprint calculations. From an ethical perspective, this study examines how the concept of explainability impacts the reliability, credibility, and auditability of AI carbon footprint models. Furthermore, it addresses how data and algorithmic biases in AI carbon footprint calculations can lead to fairness issues, particularly in the attribution and

allocation of carbon emissions responsibility. Furthermore, based on these questions, this study explores how Explainable AI (XAI) technology can help avoid these ethical risks.

Before research begin, let's first define the boundaries and methods in this study. When discussing AI ethics, concepts like explainability, fairness, transparency, and accountability often come up. Since this study focuses on using AI tools for carbon footprint calculation, we will focus on the concepts of explainability and transparency. These two concepts are related to the calculation process, database, and coefficient selection when using AI to calculate carbon footprint. Since the purpose of this study is to clarify these two concepts and to demonstrate the importance of explainability and transparency through the help of the XAI model, this study does not attempt to develop a new and appropriate personal fitable model and only applies the XAI tools or models in practice. Secondly, to achieve this research result, this study will employ a literature review and synthesis method, as well as a conceptual analysis method, as the foundation for its thinking and research. This study will clarify the importance of these two concepts through a literature review, provide explanations and definitions for each, and then demonstrate their practical application and illustration using the XAI model.

2 LITERATURE REVIEW

The issues of explainability and transparency, along with the challenges posed by algorithmic "black box," have been central concerns since the earliest applications of AI tools. In this section, the literature is reviewed from three perspectives: the positions articulated by the United Nations and UNESCO, insights drawn from major trend reports, and contributions from academic scholarship. We will use the research method of Document Analysis to compare documents horizontally to clarify how different documents interpret explainability and transparency in AI, and whether these documents raise concerns about these concepts. This information will serve as the foundation for our discussion of these two concepts in Section 3.

Readers should pay attention here: the sources considered here are framed primarily within the educational domain. This orientation is deliberate, as carbon footprint calculation constitutes an integral component of Education for Sustainable Development (ESD). If processes of carbon accounting within the ESD context are marked by unexplainability and lack of transparency, the formulation of effective and contextually appropriate decarbonization strategies becomes considerably more difficult. In other words, without reliable interpretability in AI-supported assessments, sustainability education risks producing outcomes that are normatively appealing yet practically inadequate.

2.1 United Nations and UNESCO

The United Nations has, for several years, recognized the risks associated with AI "black box" and has emphasized the need for regulatory oversight of AI tools, particularly in relation to data governance. For instance, the *Ethical Impact Assessment: A Tool of the Recommendation on the Ethics of Artificial Intelligence* (2023) highlights explainability and transparency as essential requirements to ensure accountability. The objective of such regulation is to make explicit the logic and rationale underlying AI systems' outputs and decisions, thereby ensuring that this information is accessible and that users' trust can be strengthened [3].

By 2024, UNESCO extended its concern to the pedagogical context, focusing on potential issues that may arise when teachers and students engage with AI. In its proposed framework for developing teacher competencies, UNESCO underscored that AI outputs often carry elements of randomness. As a result, educators must develop an awareness of the black box nature of AI training processes and critically evaluate the results produced by such systems [4]. Moreover, the framework elaborates that explainability encompasses the languages used in training AI, cultural representativeness, methods of data collection and utilization, as well as the adaptability of AI systems to learners of different ages and abilities [4].

With regard to students, UNESCO recommended that learners be made aware of their right to request information concerning explainability from system designers and providers [5]. Such awareness, it argued, forms a foundational competency of a human-centered mindset [5]. Similarly, in the Governing AI for Humanity: Final Report, the United Nations emphasized that AI technologies are frequently characterized by opacity and deficiencies in interpretability [6]. The report further urged member states to advance research into the transparency of AI, thereby mitigating the risk of outcomes or decisions that may exceed human capacity for responsibility or redress [6].

Most recently, in 2025, UNESCO introduced additional guidance for the academic use of AI. The report *Guidance for Generative AI in Education and Research* explicitly acknowledged the longstanding challenge: "It has long been recognized that artificial neural networks (ANNs) are usually 'black box'; that is, that their inner workings are not open to inspection. As a result, ANNs are not 'transparent' or 'explainable', and it is not possible to ascertain how their outputs were determined" [7]. Consequently, UNESCO recommended that AI providers disclose trustworthy data and computational models, including the provenance of data, the modeling techniques employed, and the types of algorithms used, thereby ensuring both explainability and transparency for end-users [7].

2.2 Recommendations and Cautions in Trend Reports

Beyond the contributions of the United Nations and UNESCO, numerous foundations and research institutions with a focus on education regularly publish reports on AI-related issues. Many of these reports likewise highlight concerns regarding the "black box" nature of AI systems and offer recommendations for mitigating associated risks.

In a report on the ethical risks of AI prepared for SURF in the Netherlands, Sack and Little observed that AI tools pose threats to fairness and justice, one major cause being the underlying algorithms themselves. Such algorithms may perpetuate biases or enable exploitative practices [8]. Similarly, Molina and Medina, in a report commissioned by the World Bank on the use of AI in higher education across South America, argued that the lack of transparency in AI tools obstructs the effective promotion of certain professional practices and constrains the optimal use of AI. They further noted that algorithmic biases can produce inequitable outcomes [9]. They identified seven potential sources of bias, among which "Data Collection and Preparation" and "Problem Definition" are particularly relevant to the domain of carbon emission calculation [9].

Hoernig and colleagues, in a report for the Lisbon Institute of Public Policy, similarly emphasized that one of the primary harms of AI use is the lack of explainability and transparency. From an educational standpoint, they argued, users must first confront the problem of AI black box in order to monitor algorithmic bias, design curricula, or integrate AI responsibly into instruction [10]. The report also noted that the European Union's AI Act already requires disclosure of AI outputs and calls for measures to mitigate risks stemming from inadequate explainability and transparency, including training to identify bias [10].

In the United States, the Department of Education's Office of Educational Technology underscored similar concerns in its 2023 report. Cardona et al. emphasized the importance of enhancing transparency and providing explicit disclosure of relevant information [11]. They recommended the development of integrated AI policies grounded in ethical and just principles, with "Promote Transparency" identified as a core pillar [11]. Moreover, the report advocated for the adoption of inspectable, explainable, and overridable AI in educational contexts. Such systems would enable teachers to understand how AI evaluates student work, why it recommends certain resources, and the rationale behind specific pedagogical suggestions [11].

2.3 Other Categories of Literature

Many scholars have also mentioned the importance of ethical characteristics such as AI explainability and transparency. For example, Pikhart and Al-Obaydi (2025) interviewed teachers and mentioned that the respondents expressed concerns about the validity and reliability of AI data [12]. These concerns include the belief that AI data may contain inaccuracies or erroneous information and the need for further verification [10]. Even those respondents who acknowledged that AI data has some reliability believe that verifying the information is important because AI can produce data that is difficult to assess for accuracy. These respondents generally believe that data generated by AI is generally unreliable. Vasquez III et al. note that AI algorithms can be subject to bias and potentially lead to unfairness, emphasizing that potential biases should be carefully considered when developing AI and its algorithms. Furthermore, attention should be paid to the lack of transparency in AI's decision-making process [13]. Vredenburgh (2024)'s research on the application of AI in public policy emphasizes that AI should be transparent to avoid harm to human rights in politics or justice [14].

To sum up, explainability and transparency of AI are important because these two ethical qualities affect every aspect of our daily lives. From the perspective of carbon emission calculations, these two characteristics are not only related to whether the calculation process can produce reasonable conclusions, but also to whether the results obtained due to this unclear process will cause harm to the user.

The reviewed literature highlights the central importance of AI explainability and transparency within the domains of education and sustainable development. The United Nations and UNESCO emphasize that, in order to uphold ethical use and accountability, the decision-making logic and computational processes of AI systems must remain understandable and accessible. Trend reports further caution that algorithmic bias and opacity may compromise fairness, and that for both educators and students, understanding the "black box" characteristics of AI is essential to safeguarding the quality of teaching and learning. Academic studies corroborate this perspective, noting that lack of transparency in AI data, reliability, and public policy applications can produce potential harms for users and society. From the perspective of carbon footprint calculation, these ethical attributes affect not only the reasonableness of computational processes but also the potential risks of adverse outcomes for users. Overall, the literature underscores that maintaining explainability and transparency in AI-supported carbon footprint assessment is foundational to ensuring ethical rigor, auditability, and fairness.

3 ON THE CONCEPTS OF EXPLAINABILITY AND TRANSPARENCY

Based on the preceding literature analysis, we have established that explainability and transparency are of critical importance for AI. The question that follows is: how should these two concepts themselves be explained? In other words, how can the concepts of explainability and transparency be rendered explainable and transparent?

Vredenburgh (2024), drawing on Kafka's novel The Trial, illustrates the dangers of untransparency and unexplainability: the protagonist is arrested, yet neither he nor anyone else knows the reason for his arrest. Although everyone insists he must be guilty, no one can specify his crime [14]. This allegory reflects the problem of AI "black box." Vredenburgh argues that explainability refers to the capacity of inference models to be understood by users. Using decision trees as an example, he notes that the branching nodes of decisions should be traceable; in this sense, AI outputs can be considered transparent. Vredenburgh thus situates these terms within the domain of political philosophy. Balasubramaniam et al. (2023) approach the concepts from an ethical standpoint, viewing transparency as a non-functional requirement that is nonetheless crucial due to its dependence on trust within system development. Both explainability and transparency are context-dependent and require careful attention to ethical principles in real-world applications [15].

The findings of Vredenburgh and Balasubramaniam align with Palacio et al. (2021), who note that although these concepts are widely regarded as important, there is no universally accepted standard, and their interpretation and application remain diverse [16]. This plurality affords significant flexibility for the design of XAI. Palacio et al. ultimately define explanation as "the process of describing one or more facts, such that it facilitates the understanding of aspects related to said facts (by a human consumer)." Compared to the previous two studies, this definition similarly emphasizes the process of being understood, though the focus differs across contexts. These conceptual insights resonate with Fedytskyi's (2025) discussion of transparency, which highlights its relation to data bias and decision-making processes. Both terms relate to the reference process users use to make decisions [17].

The above description is similar to the OECD's definition of explainability and transparency in Section 1.3 of The OECD Recommendation on AI [18]. In the web version, the OECD provides us with further explanation. Transparency emphasizes the disclosure of information during interactions, allowing users to understand AI's operations and obtain meaningful information to make more informed choices. It also promotes public and stakeholder understanding. Regarding explainability, the OECD states that "explainability means enabling people affected by the outcome of an AI system to understand how it arrived at." [19]

According to this, and considering that this research is related to carbon footprint calculation, whether the user is motivated by sustainable development education or practical needs such as carbon inventory work, when we use the terms explainability and transparency, we will primarily focus on ensuring that the AI coefficient selection and operation process can be understood. The former emphasizes the calculation process, while the latter means the source of the selected coefficients or database: both are important bases in carbon emission calculations. In our research, we will specifically consider transparency because it concerns the fairness of the calculation base and results. The 2023 EDPS (European Data Protection Supervisor) report mentioned, "The concepts of transparency, interpretability and explainability in the context of AI have no formal definition, and are sometimes used

interchangeably." [20] And according to EDPS, "A transparent AI system enables accountability by allowing stakeholders to validate and audit its decision-making processes, detect biases or unfairness, and ensure that the system is operating in alignment with ethical standards and legal requirements." [20] This is because it concerns whether the coefficients and regulations selected by AI when calculating carbon footprints are available for users to review. As for another common word, interpretability, we will not discuss it in this study because it is related to the interpretation of results rather than the actual calculation of AI when calculating carbon footprint

4 ETHICAL RISK ANALYSIS OF AI TOOLS IN CARBON FOOTPRINT CALCULATION

Building on the results of the preceding literature review, we examined how scholars have explained the concepts of explainability and transparency, both of which are primarily tied to the computational processes involved in the use of AI [21]. For example, in the case of Taiwan, the implementation of organizational carbon inventories is typically guided by five foundational steps in training and education: defining boundaries, identifying sources, performing calculations, reporting, and verification [21]. Beyond the act of calculation itself, both boundary setting and source identification are directly related to methodological choices and the selection of coefficients. If AI systems fail to provide adequate reference materials, users are exposed to the risk of being unable to discern the reliability of the data produced.

4.1 Ethical Characteristics of AI

Within ethical frameworks, AI is expected to embody, though not be limited to, the following characteristics: explainability, fairness, transparency, accountability, privacy, and security. UNESCO's thical recommendations highlight that AI-generated outcomes must not cause harm, nor should AI-driven decisions lead to irreversible consequences [3]. Although the report primarily references life-and-death decision-making scenarios, the principle holds equal importance in carbon footprint calculations, as such computations directly inform strategic planning, policy decisions, and financial commitments to emission reduction [3]. When AI ethics link transparency and explainability to accountability and responsibility, they entail whether sufficient explanations are provided to facilitate user understanding, and whether algorithms and internal reasoning processes are disclosed to the public or regulatory authorities as part of essential information transparency.

One of the primary ethical risks in using AI for carbon footprint calculations is the lack of explainability. Carbon footprints can be computed through categorical classification and subsequently presented as numerical data in public documents such as sustainability reports. However, for users lacking specialized training in carbon inventory methodologies, the calculation process and classification methods are often not their primary concern. Instead, they focus on the outcomes and numerical results, which guide their decisions in autonomous emission reduction efforts. In such contexts, transparency and explainability in the computational process demand a greater degree of trust. Therefore, when using AI tools to conduct carbon inventories, in the absence of coefficients, supporting information, and calculation processes, the data obtained poses a certain degree of risk from an ethical perspective.

4.2 The Case of Carbon Footprint Calculators

Now we can take the example of a carbon footprint calculator to illustrate the impact of this lack of interpretability risk. The carbon footprint calculator is a simple tool that helps people understand the carbon emissions generated by their activities. It has appeared on the Internet many years ago. By setting and inputting conditions, users can easily calculate the CO2e GHG they produce within a certain period of time. The carbon footprint calculator is widely accepted by users because it avoids complicated calculation processes and can obtain the corresponding carbon emissions simply by inputting the activity figures.

Although such calculators are user-friendly, reducing human activity into a formula for quantitative computation is not a straightforward task. As early as a decade ago, West et al. (2015) pointed out the inherent complexity of these calculations and their connection to behavioral change [22]. They suggested that future designs should account for changes in product prices and emission factors over time, as such changes may render the underlying methodology outdated. Designers must also navigate the trade-off between precision and usability.

Excessive complexity in data entry, pursued in the name of accuracy, risks deterring user participation.

From a user-centered perspective, Williamson (2022) reported the question which we call the "black box problem" [23]. Based on her experience, the annual household carbon footprint estimated for her family ranged from 8 to 42 tons of CO2e, depending on the level of detail in different calculators. She observed that different tools draw on varying datasets and assumptions, yet these assumptions rarely capture the specific lifestyle of an individual user relative to national averages. This underscores the necessity for calculators to provide transparent and sufficient data, references, and disclosure of computational processes.

DuPuis and Mulvaney (2024) mentioned the black box problem of this carbon footprint calculation. Although the carbon footprint calculator is a simple and convenience tool, it has been criticized on three problems: issues of accuracy and completeness in its design, its effectiveness in achieving the goal of changing individual behavior, and related scientific research issues in climate governance [24]. The first of these is related to the opacity issue mentioned in this article; the inaccuracies of carbon footprint calculators include inconsistent results, a lack of transparency into the data sources used in their algorithms, and errors even in the data used for reference. Taking meat calculations as an example, they pointed out that factors ignored by carbon footprint calculators lead to differences in carbon footprint calculations. Such differences may cause the calculation results to be distorted, and ultimately it is difficult to provide practical help for global emission reduction efforts.

The impact is not just about the difference in the calculation results, but also about applying the results to possible wrong decisions in life. Improper design of carbon reduction methods, or increasing emission reduction efforts in areas where emission reduction results are not significant, will affect the adoption and implementation of emission reduction strategies. If the carbon footprint calculator website used has a payment mechanism where users can donate to help reduce emissions, how should users ensure that their quota is in line with actual results? Therefore, the black box aspects of carbon footprint calculations in AI applications include difficulties in auditing and verification, particularly in understanding why AI models produce specific carbon footprint values. Furthermore, when no reference coefficient for emissions reduction is specified, the AI can be tricky to understand which data sources it uses to generate its results. Due to the difficulty of auditing and verification, it is difficult for users to assess whether they are biased by data, sampling or measurement, thus giving rise to fairness issues.

These ethical challenges are related to opacity and the absence of explainability, which also blur accountability and responsibility. While UNESCO's Ethical Impact Assessment framework provides a template for evaluation [3], its effective application depends on both AI developers and users proactively engaging in self-assessment. Yet when AI systems generate erroneous results or cause ethical harms, the unresolved question remains: who bears responsibility - the data providers, AI developers, model deployers, or the end-users?

5 XAI AS AN ETHICAL SOLUTION TO THE BLACK-BOX PROBLEM IN CARBON FOOTPRINT CALCULATION

As discussed earlier, the issue of the "black box" in AI decision-making poses significant ethical challenges. Because carbon footprint calculation involves the use of reference coefficients and the specification of contextual conditions, employing AI as a computational tool may generate discrepancies in outcomes - particularly when users are unable to clearly define all scopes, categories, and conditions. In such cases, whether through simplified carbon footprint calculators or AI-based computational frameworks, the results may vary substantially. To address these black-box concerns in carbon footprint analysis, the introduction of Explainable AI (XAI) offers a potential pathway for mitigating these ethical dilemmas.

5.1 The Concept of XAI

Taking IBM as an example, the company defines XAI as "a set of processes and methods that allows human users to comprehend and trust the results and output created by machine learning algorithms." According to this perspective, predictions must be accurate, the underlying techniques should be traceable, and the decision-making processes must adequately meet human needs. Proper use of XAI can enhance users' confidence in the outputs while simultaneously assisting designers in building and planning AI models with a sense of responsibility. In this respect, XAI is regarded as a key enabler of responsible AI, positioning AI models within a framework of trust and transparency [25].

EDPS further highlights that XAI embodies transparency, interpretability, and explainability – features that help users evaluate decision-making processes and understand the principles behind model predictions. EDPS also identifies two modes through which XAI facilitates interpretability in AI tools [20]:

- White Box: Employing simple and understandable models (e.g., decision trees or linear regression) that provide clear explanations of decision logic, thereby allowing decision-makers to grasp the rationale underlying specific outcomes.
- Post-hoc Explanations for Black Box Models: Offering retrospective explanations of decision processes. These include local explanations such as LIME (Local Interpretable Model-Agnostic Explanations) and SHAP (SHapley Additive exPlanations), as well as global explanations that provide broader interpretive frameworks.

Management Solutions also defines XAI as "a set of processes and methods that enable users to understand and trust the results and products created by machine learning algorithms. This discipline is crucial for an organization to build trust when using AI models, helping to characterize model accuracy, fairness, transparency and understanding of results in AI-based decision making" [26]. Their report further distinguishes between "interpretability" and "explainability." The former emphasizes human-centered understanding, defined as "the ability to explain or present in terms that are understandable to a human being," and refers to the degree to which a person can grasp the cause of a decision. The latter, in contrast, focuses on algorithms and internal logics, defined as "the dimension of a model output that describes how the output of the model was produced," demonstrating the extent to which the internal mechanics of a machine learning system can be expressed in human terms [26].

In sum, XAI may be concisely described as an approach that distinguishes itself from conventional AI by ensuring that the information it generates is interpretable and that its processes of outcome generation and decision-making can be rendered intelligible. XAI thus embodies the explainability and transparency that contemporary discourse expects from ethically responsible AI systems.

5.2 Is Such an Operation Ethically Sound?

If we apply the concept of XAI to carbon footprint calculation, and recall the discussion in Section 4.2 where the carbon calculator was used as an example, the importance of explainability and transparency in carbon accounting becomes evident. XAI, when integrated into carbon footprint calculation, should allow users to trace the sources of coefficient references, or at the very least, help them understand why AI recommends a particular mitigation strategy.

Drawing upon the three procedural steps in carbon accounting – boundary definition, source identification, and calculation – XAI's transparency primarily facilitates bias detection and diagnostic assessment. When XAI can reveal variations in model performance across different data subsets (such as geographical regions, income groups, or industrial sectors), users can scrutinize whether unfair coefficient references exist or whether location-specific sensitivities have been properly accounted for. As highlighted in the United Nations' Governing AI for Humanity: Final Report (2024), AI governance is far from evenly distributed worldwide. For instance, among 54 African countries, 48 were reported in 2024 to lack adequate AI governance mechanisms [6].

The distinctive features of XAI can provide substantial support in this context. When data inputs are adaptively trained and model algorithms optimized, users can access more accurate information and results regarding carbon footprint calculations. Enhanced precision not only improves trust but also increases the acceptability of the outcomes. Particularly significant is the capacity of XAI to furnish a "chain of evidence" in model decision-making. This includes documentation of data sources, coefficient selection, boundary settings, and constraints – key elements in carbon accounting. Such mechanisms enable AI to provide more reliable and consistent explanations, thereby helping to avoid potential greenwashing practices in carbon reporting.

In this way, by enhancing both explainability and transparency, the data produced by AI systems gains qualities of accountability and traceability. These qualities are indispensable for meeting the ethical requirements imposed on the use of AI in carbon footprint calculations.

5.3 Example: Does a Clearer Calculation Process Enhance Explainability?

Building on the concepts previously outlined, if explainability and transparency are integrated into carbon footprint calculation, users will be able to verify the ethical responsibilities tied to

accountability. In this section, two illustrative cases are used to advance the discussion:

1) Does employing the most recent version of ChatGPT-5 for carbon footprint calculations enhance the possibility of generating comprehensible results?
2) Does the use of XAI techniques – such as LIME and SHAP – offer more meaningful outcomes in carbon accounting?

Both cases are based on a carbon reduction project carried out and supervised by the author during an academic conference held in June 2025. One of the author's responsibilities in this conference was to establish a baseline for the event's carbon emissions, so that similar large-scale events in the future could benefit from a standardized reference for carbon footprint assessments. For this purpose, the research team employed Gemini to construct the computational model and adhered to ISO 14064-1 to categorize potential carbon emissions into six distinct categories. The resulting calculations were subsequently cross-verified using ChatGPT-4.

5.3.1 A Clearer Calculation Process

Taking ChatGPT as an example, in August 2025 OpenAI released GPT-5, which provides enhanced computational capacities. On August 10, 2025, the author conducted a comparative inquiry into the two versions, with particular attention given to whether GPT-5 exhibited operational features consistent with XAI principles. The test case involved paper lunchbox recycling, which was one of the subprojects in the aforementioned conference. During the event, the working team collected and recycled a total of 633 paper lunchboxes. The results highlight the differences between GPT-4 and GPT-5 in carbon emission calculations.

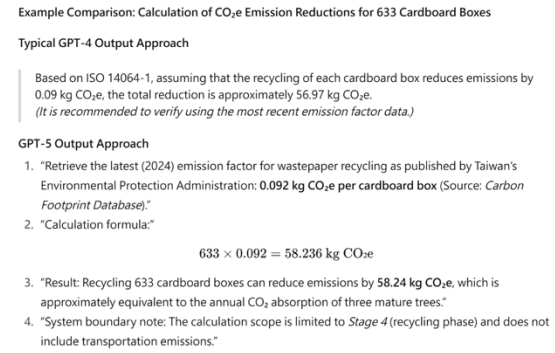


Figure 1: The example of differences between GPT-4 and GPT-5 in carbon emission calculation.

The above chart illustrates the computational differences between GPT-4 and GPT-5. While both algorithms compute "633 recycled cartons," the computational process and content presented differ significantly. Using GPT-4, we can directly obtain the basis and results of the calculation, but without the computational process and its limitations. Whereas GPT-5 went further by offering not only the basis and results but also the explicit calculation formulas and system boundary settings. Particular attention should be directed toward the notion of system boundary. This is a critical step in carbon footprint assessment, corresponding to the "boundary" concept discussed earlier. As shown in GPT-5's output (point 4 in the figure), the results are constrained within Stage 4, thereby offering substantial support and evidence regarding whether transportation should be incorporated into the calculations. This feature enables users to more clearly distinguish the categories of emissions, thereby enhancing both the clarity and accountability of the carbon accounting process.

5.3.2 Application of LIME and SHAP Models

The calculation process in Figure 1 above provides an example of transparency. Introducing LIME and SHAP can also enhance our understanding of data. This relates to the concept of interpretability, that is, whether data can be understood in a more reasonable way. This forms the second case study presented in this research.

This paper does not delve into the principles of LIME and SHAP. Related explanations can be found in the earlier discussion of XAI [26]. We can also build upon the statements made by Dwivedi and his team [27]: both methods are characterized by their ability to provide interpretations that measure the impact of having a certain value for a given feature in comparison to the prediction. Thus, when data is produced, it is no longer just numbers or results, but rather a set of symbols that can be understood and given meaning.

In this section, regarding the calculation of conference-related carbon emissions, we use Stage 3: Carbon emissions from commuting as an example. Based on Gemini's calculation results, the researcher can compare the reasonably expected amounts of carbon emissions. For instance, a scenario may be set up comparing driving a 2000cc gasoline SUV from Taichung, Taiwan, with traveling by high-speed rail. Traditional data would only provide raw figures, such as the estimated CO2 emissions produced by driving

the vehicle. However, by incorporating LIME and SHAP, the analysis can be extended to include driving habits, thus providing more meaningful explanatory insights.

We can compare scenarios constructed by SHAP: for example, comparing aggressive driving with taking the high-speed rail. If we assume a driver tends to drive aggressively, coupled with a vehicle of higher engine displacement, the total carbon emissions for a single trip could reach 28 kg CO2e. In contrast, traveling by high-speed rail would result in only 3 kg CO2e. The choice of "mode of transportation" offsets most of the emissions. When these two approaches are compared, it becomes possible to quantify and evaluate the environmental benefits of choosing high-speed rail, providing strong persuasive power.

5.4 Why Is XAI Important for Carbon Footprint Calculation? Ethical Reflections

In the two examples discussed in Sections 5.3.1 and 5.3.2, we observed that XAI provides us with clearer and more explicit explanations, making the interpretation of data more meaningful. For instance, in the case of carbon emissions from driving, if the data is merely explained at a numerical level, it does not inherently carry accountability. However, when the SHAP model is applied, the data becomes directly linked to vehicle engine displacement and driving behavior. This kind of modeling not only resonates with users but also prepares the groundwork for future carbon-related transactions by ensuring that the outcomes are understandable and fair for trading.

An article published on the Sustainability Director website reminds us that XAI has significant implications for carbon pricing. The transparency of carbon pricing implies data disclosure, and under such circumstances, it builds our understanding of and trust in mechanisms for sustainable economic transitions. XAI can provide the transparency required for carbon pricing: through its application, it can certify the transparency of the origin of carbon credits. Since XAI can offer the necessary tools and techniques to address transparency challenges in the field of carbon pricing – through evaluating carbon sequestration projects, collecting and processing complex datasets, and ensuring accountability in carbon price setting – it establishes a rigorous methodological foundation for high-quality, reliable data. This introduction of XAI provides quality-assured data through rigorous methodologies and user-centric design, ensuring that different users receive the most appropriate data. This article also addresses the issue of transparency atrophy, meaning that even with XAI, black box migrations can still occur [28].

In this sense, the use of XAI in carbon footprint calculation, based on its properties of explainability and transparency, creates the possibility of accountability and fairness in the outcomes. Thus, the introduction of XAI into carbon footprint assessment can meet ethical requirements in its application.

6 CONCLUSIONS

Since carbon footprint calculation is an essential component of sustainable development, obtaining reliable data becomes critically important. Reliable data requires clarity regarding database sources, the use of accurate and verifiable coefficients, and a transparent and reviewable calculation process. We cannot demand that every user undergo professional training or obtain certification before engaging in carbon reduction efforts, because such practices are a vital part of sustainability education and should be accessible as actions that anyone can take in daily life. Therefore, when using AI as an assistive tool, AI with explainability and transparency becomes particularly important: users need to understand how their data is generated, so that they can in turn understand how to take concrete actions to reduce emissions.

In discussing the introduction of XAI as a support for carbon footprint calculation, this study argues that explainability and transparency are crucial when using AI tools, and that XAI has the potential to meet these requirements (though its effectiveness still depends on users' professional competence and the depth of the instructions provided). While this paper used LIME and SHAP as examples of XAI applied to carbon footprint calculation, these cases are only preliminary illustrations. Future research could explore how to deepen the application of XAI or even develop new XAI methods better suited for environmental data and carbon footprint models. Furthermore, due to the limitations of this study, the concept of interpretability was not addressed in detail – only briefly referenced in examples. Since this concept relates to fairness, justice, and accountability, it is recommended for future dedicated research.

The integration of XAI technologies in the future will not only provide data with explainability and transparency in carbon footprint calculations, but also – through comparisons of different models – help users understand how they can implement emission reduction strategies in real life and even enable them to clearly measure the actual numerical outcomes of

their carbon reduction efforts. For this study was based on document analysis, while it provided some conceptual clarity, the limited AI experimentation left some room for improvement. Future research is recommended to conduct qualitative interviews to understand user experiences and design more comprehensive experiments. Through actual AI implementation and analysis of the results, we can understand how the introduction of XAI improves the concepts of explainability and transparency.

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Identification of Factors Affecting Government Job Satisfaction: A Macroergonomic Perspective from the Philippines

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Keywords: Government Employees, Job Satisfaction, Macroergonomics, Public Sector, Public Service Motivation.

Abstract: This study examines the relationships among job demands, job resources, job satisfaction, organizational commitment, and job productivity within the public sector. Grounded in the Job Demands–Resources (JD-R) framework, the research investigates how work-related factors and personal resources influence employee attitudes and performance outcomes. Using survey data collected from public servants, structural equation modeling (SEM) was employed to test the proposed hypotheses. The results indicate that job demands significantly influence job satisfaction, while job resources contribute positively to both job satisfaction and organizational commitment. Organizational commitment was found to mediate the relationship between job satisfaction and job productivity, confirming its central role in translating employee attitudes into performance outcomes. In contrast, psychological safety and public service motivation did not demonstrate statistically significant effects within the final model and were excluded from further analysis. These findings suggest that, in this context, structural and organizational factors play a more substantial role than individual motivational constructs. The study highlights the importance of strengthening job resources and fostering supportive work environments to enhance employee satisfaction, commitment, and productivity in public sector organizations. Practical implications include the need for management strategies that prioritize resource availability, role clarity, and employee engagement to improve organizational performance.

1 INTRODUCTION

Public service plays a critical role in delivering essential services such as healthcare, education, and transportation, making it a noble profession tied to national development. Many employees enter government driven by a sense of duty to the public good, linking their work to a greater purpose [1]. However, job satisfaction is critical to maintaining motivation and performance. Motivated public servants contribute to effective governance, economic progress, and public trust [2]. In the Philippine context, due to challenging problems like insufficient wages and poor working conditions job satisfaction issues are evident [3]. With this, public service quality is affected as well as organizational commitment.

In the Philippines, only 1.66% of the population represents the public servants, this small percentage makes their role critical [4]. Despite this, most experienced lack appreciation and support from the public. In addition, Filipino government workers, whose perception is negative due to political patronage and high corruption index which is in contrast India, where government jobs are honorable [5]. Additionally, they have their social and financial lives restricted by job status such as contractual employment and therefore demotivate them further [6]. With this, declination of public service motivation and low job satisfaction are affecting their job productivity.

Public Service Motivation (PSM) theory is a source of personal values that drive public employees to excel in public service. To add, high PSM levels correlate to high job satisfaction and linked performance and commitment [7]. But in developing nations such as the Philippines, PSM is not sufficient to analyze the work outcomes in scenarios where poor research production and corruption issues are prevalent [8].

In addition, other existing models that manage aspects such as recognition, job engagement, rewards, and work-life integration [9]. This study integrated PSM frameworks and macroergonomics domain

through PLS-SEM analysis to determine their influence on job satisfaction and productivity in the government. The results aim to provide the Philippine public sector with civil service policies and reforms through improving human resources and guiding future research.

2 CONCEPTUAL FRAMEWORK

This study integrates macroergonomic domains like job resources and personal resources, public service motivation (PSM) theory which is shown in Figure 1. The framework consists of 14 first-order latent variables: rewards/compensation (RC), recognition (RE), job opportunity (JO), job enrichment (JEN), job rotation (JR), organizational identification (OI), job demand (JD), psychological safety (PS), perceived organizational support (POS), public service motivation (PSM), job engagement (JE), organizational commitment (OC), job satisfaction (JS), and job productivity (JP). To which, 7 hypotheses were created. Furthermore, this integration extends PSM theory by incorporating macroergonomic perspectives in an organization through the motivational drivers to influence job satisfaction, commitment, and productivity in the public sector context.

2.1 Challenges to Job Satisfaction and Productivity in Philippine Public Service

Job resources are critical factors that enhance employee satisfaction by providing both tangible and intangible support in the work place.

- Rewards/Compensation (RC). Refers to financial incentives, salaries, and benefits that influence employee satisfaction.
- Recognition (RE). The formal or informal appreciation to which employee contributions are acknowledged.
- Job Opportunity (JO). Chances for career advancement and internal promotion.
- Job Enrichment (JEN). Which roles are meaningful, and challenging which provides opportunities for skill development.
- Job Rotation (JR). The availability of different roles or tasks that reduce.
- Organizational Identification (OI). Employees align with the organization's values and mission.

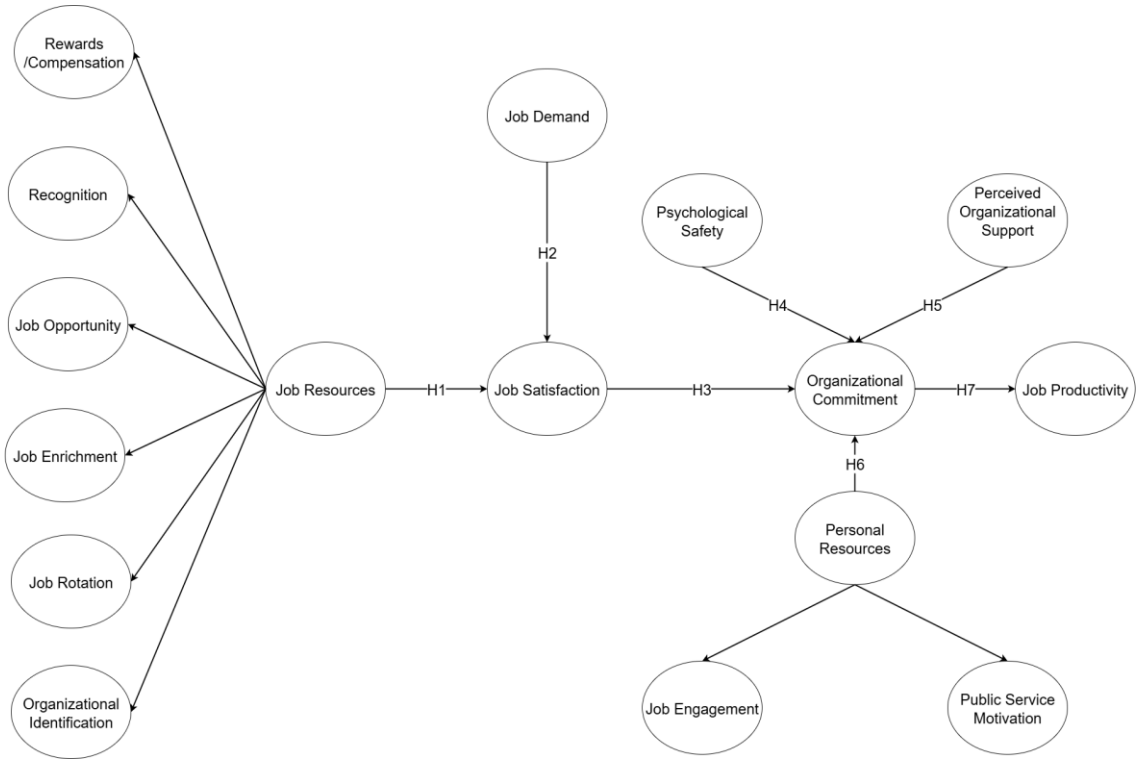


Figure 1: Conceptual framework.

- Job Demand (JD). Workload perceived by employees whether psychological or physical, which may influence stress and satisfaction.
- Psychological Safety (PS). Allows open communication in the work environment without fear of negative consequences.
- Perceived Organizational Support (POS). Employees in their organization sense that it prioritizes their well-being and acknowledges their contributions.

Personal resources are essential drivers of organizational commitment, as they shape the extent to which employees identify with their work and organization.

- Job Engagement (JE). The emotional and cognitive connection an employee has with their work.
- Public Service Motivation (PSM). The intrinsic desire to prioritize community welfare over personal gain.
- Job Satisfaction (JS). A positive affective state derived from perceived fulfillment experience from a job.
- Organizational Commitment (OC). Employees' attachment to their organization means emotional and loyalty.
- Job Productivity (JP). The effectiveness of employees in achieving work-related outputs.

2.2 Hypotheses

Based on the theoretical framework discussed, the following hypotheses were formulated:

1) H1: Job resources such as rewards and compensation, recognition, job enrichment, job opportunity, job rotation, and organizational identification are essential to improving employee satisfaction. Research in rewards/compensation using thorough compensation demonstrates that a feeling of equity in compensation improves job satisfaction [10]. In addition, recognition in the form of performance-based allowance establishes an equivalent of values that develop into high motivation [11]. And recognition contributes employee motivation by informal and formal contribution validation [12]. To add, job enrichment by adding autonomy to the job, which challenges individuals to skill improvement, enhances job satisfaction [13]. Jobs satisfaction is facilitated by employment opportunities such as career ladder and increase in responsibility [14]. The organizational identification strengthens the satisfaction level by encouraging some sense of purpose and belonging to a group [15].
2) H2: Job demand when paired with job support and control positively influence job satisfaction through moderate challenges that results to sense of accomplishment [16].
3) H3: Job satisfaction goes hand in hand with organizational commitment whereby an employee who is satisfied tends to over perform in the job than in the organization [17].
4) H4: Organizational commitment is positively influenced by psychological safety, when employees feel safe in speaking up and an environment fosters trust are loyal to the organization [18].
5) H5: Perceived organizational support likewise strengthens commitment, as employees who feel valued and supported show greater dedication and involvement [19].
6) H6: Personal resources such as job engagement and public service motivation are also critical drivers of commitment. When employees feel deeply engaged and believe their work contributes to societal good, they demonstrate stronger loyalty and resilience [20].
7) H7: Organizational commitment influences job productivity. An engaged worker who is immersed, dedicated, and satisfied with their role is closely linked to enhanced job performance [21]. Strong PSM fosters organizational commitment because employees internalize the value of contributing to society and view their roles as aligned with a larger mission [20].

2.3 Participants

This research applied a quantitative, cross-sectional design to assess job satisfaction and productivity among Philippine government workers. Data were collected via a structured online survey conducted using Google Forms. In line with [22], purposive sampling was used to recruit respondents aged 18 and above with government work experience, ensuring relevance to the study objectives. The survey link was shared through social media networks such as Viber. Instagram, and Facebook, and participants provided informed written consent before taking part in the study. Of the 268 individuals who completed the survey, only 253 responses were retained for analysis, excluding incomplete or non-government entries, as shown in the following Table 1.

Table 1: Sociodemographic profile.

Characteristics	Category	n	%
Gender	Male	96	37.9
	Female	157	62.1
Age	18 to 24 years old	37	14.6
	25 to 34 years old	115	45.5
	35 to 44 years old	55	21.7
	45 to 54 years old	30	11.9
	55 to 64 years old	16	6.3
	> 64 years old	0	0
Job Status	Permanent	164	64.8
	Casual	19	7.5
	Contract of Service	53	21.0
	Job Order	17	6.7
Work Experience	< 1 year	40	15.8
	1 to 3 years	50	19.8
	4 to 6 years	40	15.8
	7 to 9 years	37	14.6
	> 9 years	86	34.0

2.4 Measurements

In this study, the questionnaire used as indicated in the supplementary material was adapted from different studies. It consisted of 65 items distributed across 14 latent variables: job demand, psychological safety, perceived organizational support, rewards/compensation, job engagement, job enrichment, job opportunity, job rotation, recognition, organizational identification, job satisfaction, job productivity, organizational commitment, and public service motivation. A 5-point Likert scale was employed to assess each construct on a scale from 1 (strongly disagree) to 5 (strongly agree), designed to capture the level of agreement with statements reflecting various job-related and organizational perceptions.

2.5 Structural Equation Modeling

The structural equation modeling (SEM) was used in this study to analyze the causal relationships among variables affecting job productivity and satisfaction in the Philippine government, a method well-suited for examining human and organizational behavior. The use of partial least squares structural equation modeling (PLS-SEM) for exploratory models with multiple constructs and to handle smaller sample sizes was due to its suitability [23]. This approach also accounts for measurement error and can test both the structural and measurement models simultaneously. SEM has been widely applied in government research; for example, [24] used it to examine local employees' technology adoption, highlighting performance expectancy, social influence, and facilitating conditions as key predictors. Drawing from these precedents, the present study utilized SmartPLS v4.0 to evaluate the proposed extended PSM framework and examine the strength of causal relationships influencing job satisfaction and productivity among Filipino government workers.

3 RESULTS

3.1 Results of Initial SEM

Figure 2 illustrates the initial SEM, showing the influencing factors of Filipino public servants' job satisfaction. The model comprises 14 latent variables and 65 indicators. Following established guidelines [23], [25], [26], factor loadings below 0.70 were considered weak and excluded to ensure reliable measurement of latent constructs. Similarly, p-values greater than 0.05 were deemed statistically insignificant relationships [25] and were removed to enhance model fit. These insignificant paths are depicted as dashed lines in the model, indicating weak or non-significant relationships that did not meet the threshold for inclusion in the final analysis.

Table 2 shows the results from both the initial and final SEM models and responses by descriptive statistics. All measured items demonstrated factor loadings above the accepted threshold of 0.70, confirming satisfactory indicator reliability in accordance with [23]. However, all final indicators under Psychological Safety (PS), as well as the POS1 item under Perceived Organizational Support (POS), were excluded from the model due to their insignificant factor loadings, as shown in Table 3.

Using the heterotrait–monotrait ratio (HTMT) the measurement model and variable correlations were evaluated to establish discriminant validity alongside the Fornell–Larcker criterion (FLC) [27]. According to the FLC, it is acceptable when diagonal values exceed the corresponding vertical and horizontal values [25]. Further states that when HTMT values are below 0.85, discriminant validity is established [28]. In this study, demonstrating adequate reliability and discriminant validity, all HTMT and FLC values passed the established thresholds.

Model fit was assessed to validate the proposed model. All parameter estimates met or exceeded their respective thresholds, confirming the model's suitability. The SRMR value was 0.064, below the 0.08 cutoff, the Chi-Squared to degrees of freedom ratio was 3.528, within the acceptable limit of less than 5.00, and the NFI was 0.906, exceeding the 0.90 benchmark, as shown in Table 4.

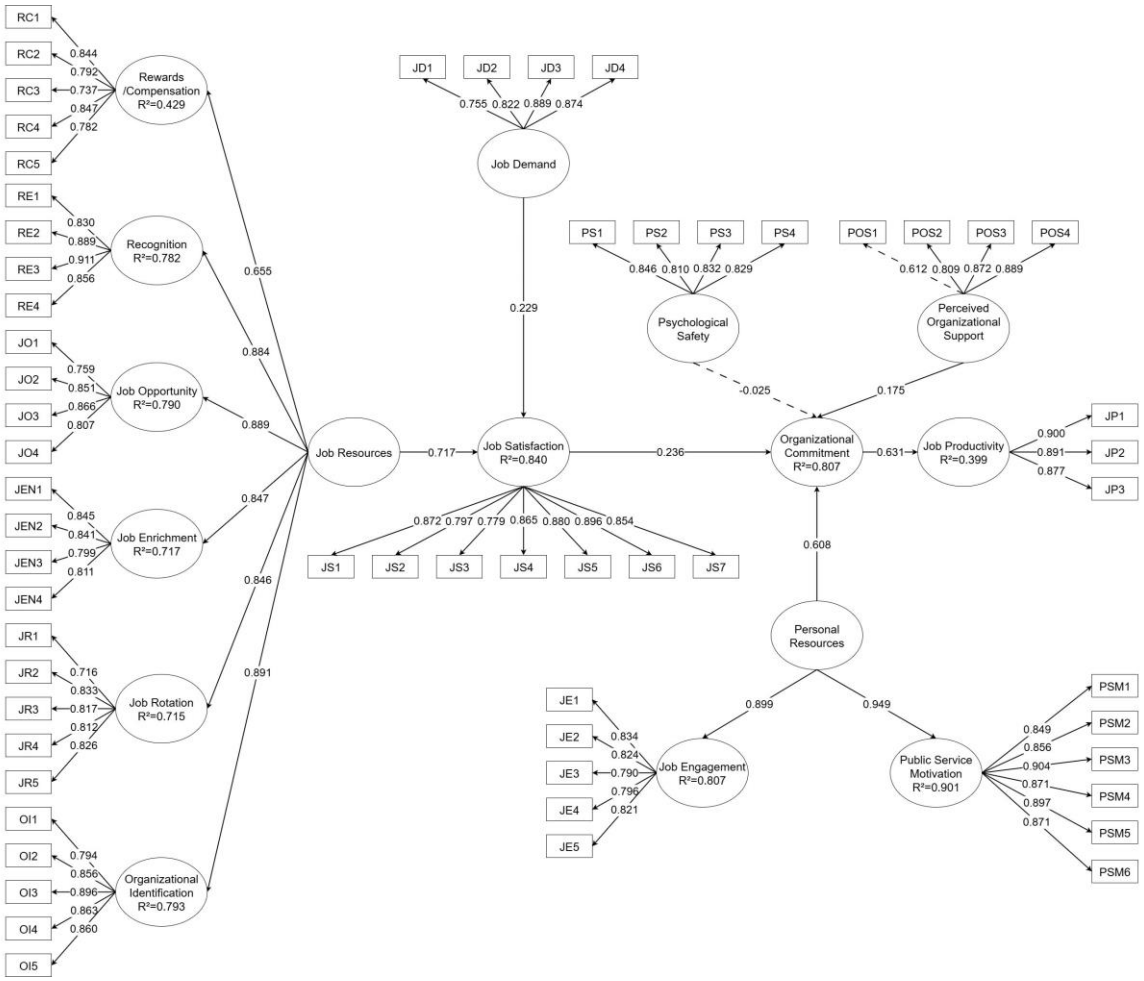


Figure 2: Initial SEM.

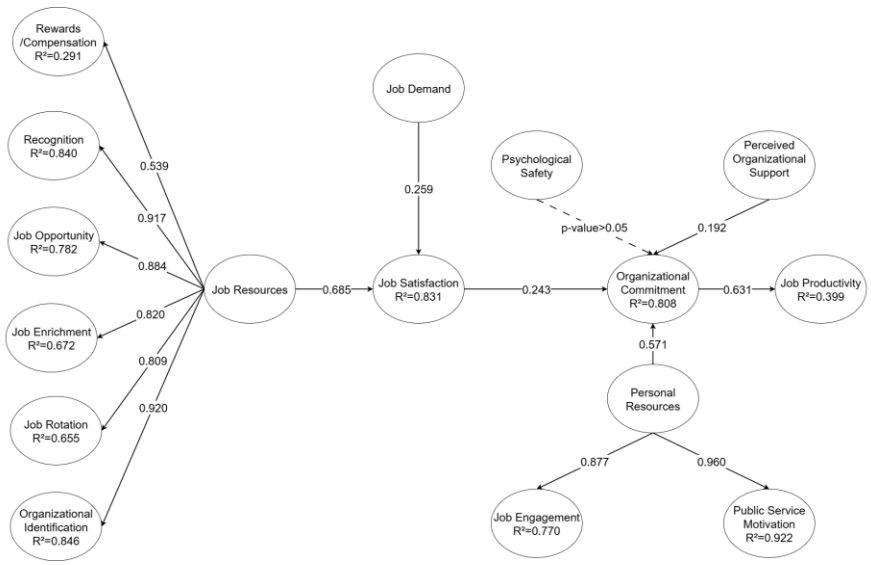


Figure 3: Final SEM.

Table 2: Indicator data analysis.

Variable	Item	Mean	Standard Deviation	Factor Loading	
				Initial	Final
JD	JD1	3.842	0.997	0.755	0.755
	JD2	3.964	0.873	0.822	0.822
	JD3	4.012	0.846	0.889	0.889
	JD4	3.988	0.860	0.874	0.874
PS	PS1	4.209	0.800	0.846	-
	PS2	4.312	0.750	0.810	-
	PS3	4.111	0.887	0.832	-
	PS4	4.111	0.873	0.829	-
POS	POS1	3.553	1.150	0.612	-
	POS2	4.024	0.893	0.809	0.822
	POS3	3.941	0.928	0.872	0.891
	POS4	4.154	0.855	0.889	0.897
RC	RC1	3.636	0.987	0.844	0.846
	RC2	3.494	1.043	0.792	0.789
	RC3	3.186	1.340	0.737	0.738
	RC4	3.561	1.086	0.847	0.849
	RC5	3.577	1.121	0.782	0.780
JE	JE1	4.557	0.696	0.834	0.837
	JE2	4.399	0.719	0.824	0.826
	JE3	4.431	0.765	0.790	0.782
	JE4	4.154	0.827	0.796	0.794
	JE5	4.545	0.691	0.821	0.825
JEN	JEN1	4.099	0.840	0.845	0.850
	JEN2	4.182	0.847	0.841	0.833
	JEN3	3.897	0.935	0.799	0.787
	JEN4	4.111	0.878	0.811	0.821
JO	JO1	4.047	0.981	0.759	0.752
	JO2	3.838	0.950	0.851	0.851
	JO3	3.779	0.953	0.866	0.868
	JO4	3.921	0.894	0.807	0.810
JR	JR1	3.530	1.154	0.716	0.710
	JR2	3.818	0.961	0.833	0.838
	JR3	3.874	0.966	0.817	0.812
	JR4	4.186	0.853	0.812	0.808
	JR5	3.964	0.913	0.826	0.833
RE	RE1	4.036	0.913	0.830	0.830
	RE2	3.933	0.978	0.889	0.890
	RE3	3.877	0.918	0.911	0.912
	RE4	3.581	1.106	0.856	0.854
OI	OI1	4.099	0.756	0.794	0.791
	OI2	4.356	0.754	0.856	0.856
	OI3	4.130	0.761	0.896	0.896
	OI4	4.328	0.754	0.863	0.864
	OI5	4.075	0.932	0.860	0.861
JS	JS1	3.972	0.921	0.872	0.873
	JS2	3.640	1.022	0.797	0.794
	JS3	4.123	0.823	0.779	0.778
	JS4	3.992	0.941	0.865	0.866
	JS5	3.917	0.927	0.880	0.881
	JS6	3.783	1.020	0.896	0.896
	JS7	4.055	0.878	0.854	0.855
JP	JP1	3.925	0.875	0.900	0.900
	JP2	4.024	0.902	0.891	0.891
	JP3	3.925	0.870	0.877	0.877
PSM	PSM1	4.474	0.680	0.849	0.849
	PSM2	4.423	0.732	0.856	0.856
	PSM3	4.577	0.634	0.904	0.905
	PSM4	4.518	0.692	0.871	0.871
	PSM5	4.451	0.713	0.897	0.897
	PSM6	4.439	0.718	0.871	0.871
OC	OC1	4.435	0.712	0.876	0.876
	OC2	4.253	0.824	0.834	0.834
	OC3	4.340	0.702	0.894	0.894
	OC4	4.415	0.664	0.885	0.884
	OC5	4.328	0.769	0.860	0.861

Table 3: Convergent validity.

Variables	Cronbach's Alpha	CR	AVE
Job Demand	0.855	0.903	0.700
Job Engagement	0.872	0.907	0.661
Job Enrichment	0.844	0.894	0.678
Job Opportunity	0.839	0.892	0.675
Job Productivity	0.869	0.919	0.791
Job Resources	0.956	0.961	0.605
Job Rotation	0.861	0.900	0.643
Job Satisfaction	0.936	0.948	0.723
Organizational Commitment	0.920	0.940	0.757
Organizational Identification	0.907	0.931	0.730
Perceived Organizational Support	0.840	0.903	0.757
Personal Resources	0.936	0.946	0.637
Public Service Motivation	0.939	0.952	0.766
Recognition	0.895	0.927	0.761

Table 4: Model fit.

Goodness of Fit Measures of the SEM	Parameter Estimates	Minimum Cutoff	Recommended by
SRMR	0.064	<0.08	[29]
Chi-Squared	3.528	<5.00	[30]
NFI	0.906	>0.90	[31]

4 DISCUSSIONS

Results showed a positive significant relationship between job resources and JS ($\beta = 0.685$, $p < 0.001$). This suggests employee satisfaction stems from multiple interrelated resources rather than a single factor. Among job resources, RC was critical. Employees satisfied with pay equity, benefits, and performance-based rewards reported higher satisfaction [32]. RE, including praise and awards, also enhanced satisfaction by making employees feel valued [33]. JO, such as training and clear progression, were important for long-term satisfaction [34]. JEN, involving autonomy and meaningful work, positively influenced satisfaction [35]. JR, providing exposure to different roles, reduced monotony and increased engagement [36]. OI was a strong predictor of satisfaction, reflecting employees' pride and loyalty to their organization [37]. Overall, these results confirm that job satisfaction arises from a combination of compensation, recognition, growth opportunities, enriched roles, job variety, and organizational pride.

And between OC and JP ($\beta = 0.631$, $p < 0.001$), a positive significant relationship was found. This aligns with, showing that committed employees tend to align with organizational goals, put in extra effort, and feel a strong sense of belonging which leads to higher productivity [38]. This study extends those findings to the Philippine public sector, supporting [39] who emphasized the importance of commitment for productivity across different economic contexts.

Personal resources also positively influenced OC ($\beta = 0.571$, $p < 0.001$). Employees who clearly understood their roles, embraced challenges, and aligned with organizational values demonstrated stronger commitment. This supports, who found that JE fosters belonging and loyalty, [40] and [41], who noted that PSM deepens attachment to the organization. Taken together, these results show that PSM and job engagement foster organizational commitment by enhancing satisfaction and sustaining long-term dedication.

JD showed a positive significant relationship effect on JS ($\beta = 0.259$, $p < 0.001$). Respondents reported higher satisfaction with reasonable workloads, supportive environments, helpful supervisors, and collaborative teams. This supports, who found balanced demands and strong social support reduce strain and boost satisfaction [42].

JS also positively influenced OC ($\beta = 0.243$, $p < 0.001$). Employees satisfied with compensation, benefits, leadership, career development, and recognition showed stronger commitment. This

echoes, who found that in Southeast Asian public service, satisfaction and commitment reinforce each other. Job satisfaction fosters loyalty and alignment with organizational goals [43].

POS positively affected OC ($\beta = 0.192$, $p = 0.001$). Employees who felt supported by supervisors and their organization, including development opportunities and work resources, showed stronger commitment [44]. Also found that perceived support reduces stress and fosters attachment by improving emotional well-being and work-life balance.

Lastly, interestingly, no significant effect between PS and JS ($\beta = -0.025$, $p = 0.692$). Despite respondents feeling their ideas were valued and supported, this did not translate into increased satisfaction. Unlike [45] findings in individualistic cultures where open communication drives satisfaction, psychological safety in the Philippine public sector may be less distinct, as collectivism and group harmony already provide baseline security.

4.1 Theoretical Implications

This study contributes theoretically by offering a holistic framework linking job satisfaction, job productivity, and organizational commitment in the public sector, which is an area often overlooked in prior research. It highlights how job resources, personal resources, job demand, and perceived organizational support interact to shape employee outcomes. By identifying key drivers of satisfaction and commitment, the model informs strategies for improving public sector performance. The framework not only deepens understanding of employee behavior in government settings but also offers a basis for future studies across other sectors and organizational contexts. Furthermore, in the context of the Philippines, the PLS-SEM utilization provides a deeper causal relationship in the public sector and introduces new local research, as shown in Figure 3.

4.2 Sustainable Managerial Implications

The findings offer critical implications for enhancing job satisfaction, productivity, and commitment in the public sector. Since satisfaction is shaped by resources such as compensation, recognition, career development, and meaningful work, agencies should prioritize equitable pay, growth opportunities, and role enrichment. The results also emphasize the role of perceived organizational support, job engagement, and public service motivation in strengthening commitment, underscoring the need for supervisors to foster inclusive, supportive, and purpose-driven environments. With this, it aligns with United Nations SDG 8, which focuses on decent work and economic growth, in the context of the Philippines. Integrating these drivers into the workplace impacts job satisfaction, which translates in excellent public service through a transparent leadership with shared cultural values.

4.3 Limitations and Future Works

Although this study explores government job satisfaction and offers new insights, some limitations are noted. It could negatively affect generalizability because the study that focuses on Filipino public servant it is proposed represent cross-sectoral or country comparisons. And also, use a data which is self-supported may introduce potential bias, in which future studies could incorporate a more comprehensive view thought observational data and interviews alike. And while this study utilized PLS-SEM, it is noted that other areas for public sector contexts like digital transformation offer an evolving area to explore.

5 CONCLUSIONS

This study examined the relationships among job demands, job resources, job satisfaction, organizational commitment, and job productivity within the public sector using the Job Demands–Resources (JD-R) framework.

The findings confirm that job demands and job resources play a significant role in shaping job satisfaction, while job resources also directly contribute to organizational commitment. Organizational commitment was found to mediate the relationship between job satisfaction and job productivity, highlighting its central role in translating employee attitudes into improved performance outcomes.

In contrast, psychological safety and public service motivation did not demonstrate significant effects in the final model, suggesting that structural and organizational factors may outweigh individual motivational constructs in this context.

These results contribute to the JD-R literature by providing empirical evidence from the public sector, emphasizing the importance of resource-based management strategies in enhancing employee performance. The study also extends existing research by clarifying the mediating role of

organizational commitment in linking satisfaction to productivity.

From a practical perspective, public sector organizations should prioritize strengthening job resources, including role clarity, engagement, and organizational support, to improve employee satisfaction and commitment. Such strategies can lead to more effective and sustainable improvements in job productivity.

Future research may explore longitudinal designs, cross-sector comparisons, and the integration of additional psychological and organizational variables to further refine the explanatory power of the model.

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