Wireless Body Sensor Networks: A Review of Energy-Saving Techniques and Security Challenges

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Abstract: There are many technologies used in monitoring patients and providing healthcare to them. One of the most important systems that have been used is wireless body sensor networks. These networks collect a set of physiological data related to the body and then process it. However, this type of network faces many problems, one of which is the small size of this type of network, which leads to energy consumption. Therefore, this type of problem leads to short battery life of the sensor node. Therefore, this type of paper has been studied for the purpose of analysing or providing current improvements in energy efficiency. Energy is also consumed when security is provided in because this type of processor requires consuming a large amount of energy. Therefore, this paper was presented, which covered research from 2019 to 2024. This research focused on providing key solutions to solve the energy problem, as well as the energy-saving protocols used, the hybrid methods that were used, and the machine learning processes that were used to improve energy methodologies and also provide security. For the network, the results revealed during this type of studies that the network lifetime was improved by 60 to 70% using hybrid algorithms, while routing algorithms based on energy consumption processes that are based on groups have a consumption rate of 30 to 50% compared to standard methods. In addition, there are security features that play a fundamental role in this type of network, such as the use of encryption and simple authentication procedures, which played an important role in achieving a balance between energy consumption and data protection. These references or the results obtained and the comparison of research among them are considered a reference for practitioners who seek to improve security and energy consumption in wireless sensor networks.

1 INTRODUCTION

One of the important technologies that has spread recently and that has revolutionized several fields, including the field of health care, is the wireless sensor network. This network provides, instead of performing quick surgical operations or having patients go to the hospital, remote monitoring of the sick or injured person in terms of many aspects, including measuring the heart rate, as well as the percentage of oxygen in the blood and measuring the back [1].

This type of network does not provide the capabilities and diagnosis in several details, including the fields of pellet, but the biggest challenges that are considered difficult and that face this type of network are the battery life due to the small size of this type of network, starting from the network in which you see the battery budget as a problem in addition to other security problems, as it requires replacing the battery every 48 to 72 Javaod was according to the type of operations that were done in this type of network [2], [3]. In terms of the presence of operations in this network and as a result of its consumption of the amount of energy due to the lack of data with important data related to the patient, therefore this type of data needs several points, including the useful improvement of energy, the useful goal, and also the importance of saving data and providing security for the transfer process, and this requires a type of algorithms that are the least little only for energy [4] so this paper will clarify it, dedicated and specific to analyze and study many researches in terms of some researches, it is an algorithm used in providing energy, some algorithms used in the processes of providing security during the transfer of patient data to the source, which represents to the hospital

This research presents a set of previous studies that were proposed to address the problems of this type of networks, such as increased energy consumption and the network’s lifespan, where protocols were used. Some of these studies used mathematical models, and some used smart mechanisms and methods to increase the network’s lifespan and extend the battery life. Some of these studies also studied the use of encryption mechanisms and other methods in terms of providing security during data transfer.

Many studies have been conducted on this type of networks. During the past five years, many researchers have faced challenges in designing this type of networks and the problems encountered during implementation. This type of modern survey studies that have now been put forward for this research have studied several aspects, including the first is the energy consumption processes present in this type of networks through the sensor unit or during the processing process, data transfer and deletion of duplicate data. All of these processes lead to the consumption of a certain amount of energy. Therefore, the process of improving these components and extending the life of the network and reducing energy consumption is considered the problem or the proposed research that is currently being studied. Some of them have used sources such as environmental authentication such as the use of solar energy or electromagnetic energy, and some have used algorithms for the purpose of reducing energy consumption during the data processing process [5]. There are many protocols that have been proposed by researchers to increase energy efficiency. Among these protocols are energy-efficient routing protocols, which work to reduce the existing energy consumption and reduce congestion that occurs during the process of data transfer in the network. There are some algorithms or strategies that have been proposed to also reduce energy consumption and increase the network’s [6]. In addition, there is research that has been proposed by researchers to also provide data security. Therefore, achieving these two elements, which are reducing energy consumption and providing security, is considered a matter of utmost importance to increase the lifespan of this network. Also, data integrity, that is, the process of providing security during network transfer during data transfer in the network, is considered one of the problems facing this network, as the process of data transfer while providing security also consumes energy [7]. Therefore, some types of researchers have studied appropriate algorithms to provide secure data transfer in medical devices, increase the network’s lifespan, and verify data privacy during transport [8].

Providing confidential techniques to maintain the privacy of data during its transfer, especially patient information, and providing security measures and protecting data during storage. These techniques were discussed in this paper, in addition to authentication processes, which are considered important in ensuring the accuracy of data and deleting incorrect data or information during its transfer through the network [9].

The research paper is organized as follows: Section 2 discusses an overview of wireless sensor networks. Section 3 addresses the energy consumption aspect of this type of network. Section 4 addresses the methodology and security according to the presented research and analysis of the results. Section 6 is the conclusions and future work. This research focuses on the importance of the problems that exist in this type of wireless sensor networks. The most important of these problems are energy consumption and security in this type of network due to the privacy and accuracy of the data, as it is vital data.

2 OVERVIEW WIRELESS BODY SENSOR NETWORKS (WBSNS)

Medical emergencies and monitoring of patients' health have become a sensitive and extremely important matter in recent times. Therefore, this type of network has provided a broad view in this field, as medical information is transferred to the hospital, which facilitates its processing or early intervention in terms of treating the patient remotely or the need to perform surgical operations. However, the energy consumption processes in this type of network are considered due to its zero size in the manufacturing process for the purpose of ease of use and carrying by users, and also due to the use of special protocols for data transfer and protocols for providing information [10].

Therefore, cooperation is proposed in various disciplines in order to innovate a way to provide security and reduce energy consumption during the process of transferring and processing data in this type of network [11].

2.1 Applications and Use Cases of (WBSNs)

There are many fields in which information technology has been used, and among these fields is the field of health care, as this type of network used in health care uses many sensor nodes that are installed inside or outside the body, according to the physiological standards that have been set, which transmit data from inside the body or the body's surroundings wirelessly. Among the most important results or applications that have been used in this type of network from research articles, according to the following.

2.2 Healthcare Monitoring and Elderly Care

This type of network is widely used, especially for the elderly, for the purpose of monitoring the movement of the elderly or related health problems. Thus, the availability of this type of network is real-time monitoring of patients or the person who is using this type of device and collects data and sends it to the medical staff, which allows the hospital or medical staff to take the necessary measures in a timely manner in the event that the injured or sick person, except for the user of this type of network, is exposed to a sudden illness or falls during movement, and according to the type of proven use of this type of wireless sensing network, meaning that it works to send data instantly and effectively to the medical staff for the purpose of entering and taking the necessary action [12].

2.2 Data Security and Privacy

Several hybrid encryption algorithms combining Blowfish, AES and RSI were used to protect sensitive information to avoid data security concerns during its transmission from the hospital in the same serial order, ensuring smooth and secure access [13]. One of the methods used in encryption processes is the use of elliptic curve ciphers and also the use of fuzzy region algorithms in order to protect data during the encryption process and transfer it from the patient to the hospital in a secure and effective manner using real time [14]. Another type of encryption and data protection methods during transmission is the process of using, managing, and authenticating keys to provide security for the patient's private data, which reduces energy consumption during the processing and transmission process. One of these methods is the use of the blockchain [15].

3 ENERGY CONSUMPTION IN WBSNS

Due to the short battery life in this type of network, the process of energy consumption is still a big problem despite its importance in this type of device. Therefore, while there are many studies that have been presented containing this topic using various algorithms or methods to reduce energy consumption.

3.1 Energy Consumption Components

3.1.1 Components Affecting Energy Consumption

One of the important and basic parts of this network is the sensor unit, as this unit collects data used by patients, which varies according to the type of sensor inside or outside the body [16], such as measuring heart rate, temperature, blood pressure, or monitoring the patient in the event of a fall. The second type of these basic parts is the signal processing process, which is done by deleting duplicate data and removing the fact that this type of data is sensitive [17] so it requires a process of filtering and strengthening the signal and removing the noise associated with this type of data so that it does not lead to errors during the monitoring process. The basic and third important element used in this is the network battery, which is considered an important source for all components of this type of network [18].

3.1.2 Strategies to Reduce Energy Consumption

- A method has been proposed to reduce energy consumption in the event that the sensor is not used and convert it to low energy, i.e. in the event of inactivity. This method is called the Duty cycle [19].
- The second method that has been used is instead of all nodes in the network sending data, it is sent by a node responsible for collecting data and reducing or deleting duplicates and sending them. After that, the sending process is done [20].
- The third type that has been proposed is taking data samples for the purpose of monitoring the patient's condition [21]. A method has been proposed to reduce energy consumption in the event that the sensor is not used and convert it to low energy, i.e. in the event of inactivity. This method is called the work cycle. The second method that has been used is instead of all nodes in the network sending data, it is sent by a node responsible for collecting data and reducing or deleting duplicates and sending them. After that, the sending process is done. The third type that has been proposed is taking data samples for the purpose of monitoring the patient's condition. The last type that has been added is the process of harvesting energy in order to consume and reduce energy consumption in the body. This is done by converting the surrounding energy from body heat, noise, or movement into electrical energy. Energy harvesting techniques include the following:
- Thermoelectric Generators (TEGs): This type of generator utilizes the conversion of heat between the body and the surrounding environment into electrical energy, which recharges the battery or extends the battery life of the sensor network
- Piezoelectric Harvesters This type of sensor converts body movement into electrical energy—that is, the mechanical pressure resulting from the body movement of the person using this type of sensor into electrical energy, which can be used to extend the life of the network.
- Solar Harvesting: This type uses solar cells to convert light into electrical energy to recharge or extend the battery life [22], [23].

3.2 Optimization Techniques

Reducing energy consumption and increasing network efficiency has been proposed many investment mechanisms used to solve these problems, including improving the locations of sensor nodes, i.e. [25].

Their ideal distribution in the body, as this method provided better performance for a specific type of sensors in the body, i.e. a specific node is the one that collects data, reduces repetitive data, removes noise and sends data. Among the improvement methods that have been proposed are the following [26]:

1) Genetic Algorithms (GA). But the strategy of applying religious algorithms, where this method was inspired by the principles of evolution present in nature, where its processes included such as selection, mutation and mating, with the aim of obtaining the optimal solution. This type was applied in order to improve the sensor locations and choose the best paths for the purpose of sending data, then it leads to reducing energy consumption instead of the wrong repetitive processes.
2) Fuzzy Logic. A technique called fuzzy region was used which demonstrates a rational approach by setting principles and a threshold to be followed while selecting the path or nodes responsible for sending data. This method led to reducing the energy consumption of the nodes during the processing and transmission process from the patient to the medical center.
3) Understanding Game Theory. Game theory, which is a branch of mathematics that studies how to make decisions in situations by analyzing the existing situation, has been used. Therefore, this type of method has been used and applied in the field of wireless communication networks to facilitate the selection of the best path and reduce energy consumption in the nodes.
4) Cross-Layer Optimization.Description: Cross-layer optimization refers to the interaction between various levels of network This technology is used to synchronize data transmission across the layers of wireless sensor networks: the physical layer, the Internet layer, and the application layer.

5) Dynamic Adaptive Techniques.This technology uses a dynamic method on various network data by changing the duty cycle and the data transmission power and the data transmission rate. That is, the data is sent and processed according to the requirements of the actual need of the person [27].
6) Ant Colony Optimization (ACO). This method was derived and used through the ant nest technology, where the technology was used to find the best paths to reach food based on the smells left by ants searching for food. Therefore, this type of algorithm was applied in wireless networks to find the best path to send and direct data, which leads to reducing the amount of energy consumed during the transmission process.
7) One of the techniques used to improve or reduce energy consumption and choose the best paths is the fish or bird swarm technique, where the phenomenon of how these swarms move to search for food was used by improving the candidate solutions according to certain criteria that are set by these groups for the purpose of choosing the best possible solutions and choosing the best path to obtain food. Therefore, this type of technique used by these swarms was applied for the purpose of choosing the best node in the network and choosing the best path, which reduces the consumption of dead energy in the network.
8) Grey Wolf Optimization (GWO). One of the techniques that has been applied in this type of network and which has been inspired by the method of hunting gray wolves, where during this group a social structure and hunting behavior are arranged to find the optimal solution. This idea was used by choosing the best node in the network and choosing the best paths, which leads to reducing energy consumption during the transfer of data to the medical center or during its collection [28].

3.3 Routing Protocols

In order to send the data collected through the wireless sensor networks from the patient's body, which are inside the body or distributed around the patient's body, protocols are needed to direct them. Therefore, routing protocols were used to send the data and improve the network condition in the body area [29].

Key Challenges in WBSN Routing:

- Limited Energy. Because this type of network is small in size, it uses a small battery, so the process of saving energy and reducing its consumption is considered a very important task.
- Dynamic Topology. One of the challenges facing this type of network is the movement of the node or changing its location in the patient’s body, or the patient is naturally moving, which leads to a frequent change in the distribution of the network’s nodes and their distance from the center.
- Real-time Requirements. This type of network considers the process of poisoning data in a timely manner as the basic and urgent condition, so it requires that the access time of this data be made as short as possible and the consumption of a certain amount of energy.
- Security and Privacy. One of the basic and important processes is the process of providing protection for data during the transfer process, as this type of data is sensitive and related to the patient. Therefore, the highest levels of protection must be provided for it during the transfer process [30].

Common Routing Protocols for WBSNs:

1) Flat Routing. This type of protocol is effectively used in sensor networks that cover a small geographical area, as it is easy to implement and consumes a small amount of energy, so it is not suitable for large-scale networks. One of this type Direct Sequence Spread Spectrum (DSSS) [31].
2) Hierarchical Routing. This type of protocol is used with large networks, as it performs more complex operations, so it consumes a large amount of energy, which can sometimes lead to the failure of some nodes in the network as a result of the energy consumption in them.: Cluster-based routing, Minimum Spanning Tree (MST) routing.
3) Location-based Routing. This type of protocol is primarily based on determining the location of nodes in the network, so the data transmission process is accurate, which leads to consuming a smaller amount of energy. However, the result requires determining accurate information about the location, so

this type of protocol is difficult to implement in some types of wireless sensor networks, depending on the type of node distribution in the patient's body.Examples: Geographic Routing, Distance Vector Routing (DVR) [32].

4) Data-centric Routing. Advantages: This type of protocol has the ability to adapt to changing data patterns, which leads to improving the network's efficiency in the data transfer process. However, as a result, it requires a large amount of data to process, which then leads to the consumption of a larger amount of energy.Examples: Interest-Driven Routing (IDR), Data-Oriented Routing (DOR).
5) Hybrid Routing. This type of protocol combines several different approaches, i.e. they are derived from other protocols, which provides flexibility in data transfer. However, as a result, the implementation process of this protocol becomes difficult and complex, as it combines several approaches at the same time. Cluster-based routing with location-based optimizations [33].

3.4 Energy Efficient Routing Protocols

There are several protocols that have been proposed to improve the efficiency of wireless network sensors, which leads to an increase in the data transfer process with the least amount of errors. Among these protocols is the MAC protocol, which provides a permanent connection and combines the channel division protocol according to a time slice. This protocol is able to reduce the percentage of energy consumption by 40% compared to other protocols as a result of the techniques it follows in the process of collecting data, processing it, and sending it to the final destination [34].

There are some types of protocols that work intelligently and can be called intelligent routing protocols that take into account the network structure and the distribution of nodes in it and examine the amount of energy available in each node. Before sending data, it ensures the node’s ability to work and complete the task that was assigned to it [35], [36].

There are some types of protocols that are primarily concerned with the importance of data distribution, i.e. network technology and how nodes are connected to each other for the purpose of reducing energy consumption and increasing the network’s lifetime. This type of protocol is the topology control protocol [5].

Although many studies have been proposed to address the problems related to the process of increasing the network lifetime and transferring data securely, each research contains a loophole or a research problem that has not been addressed. Some research has primarily addressed increasing the network lifetime without providing the matter, and some research has addressed providing security during data transfer at the expense of extending the network lifetime, as there are some protocols that have been designed in the wireless speaker network to save energy and increase its lifetime and are used in the Internet of Things. [46]. The ORS-NCM The routing protocol studied in this research paper was used, as it depends on the heat energy emitted from the body and also avoids congestion during the process of sending data in the node [47]. In this research, the issue of energy consumption was addressed, but it did not clearly explain how the proposed result compares with other available techniques or how security is provided during the data transfer process [48]. The Hybrid Tunicate-Whale Swarm Optimization algorithm is used for improved performance [49]**,** but the problem of designing energy-aware In this type of research, algorithms were proposed that depend on the use of the duty cycle, meaning that if the nodes are not consuming or using the purpose of transferring data, they are in a state of hibernation. Therefore, energy consumption was reduced, and according to the type of operations that the nodes perform, they are operated [50]-[56]**.**

4 METHODOLOGY

The methodological framework used in this work is called PRISMA 2020, which was used among a group of 1237 articles from IEEE and Scopus. 78 peer-reviewed research papers were acquired based on the type of research presented in terms of focusing on the efficiency and energy of networks. They were experimentally verified through preliminary models. The excluded studies included theoretical models without application, which numbered 412, and some of them were non-English publications, usually 53. The preliminary data for quantitative measures such as the percentage of energy consumption and encryption time were extracted, and the results were compared with each other in the Table 1 and Table 2.

Table 1: Energy efficiency optimization techniques in WBSNs.

Author	Objective	Method	Advantages	Disadvantages
Shahrokhi, S.M. (2013) [37]	Reduce energy consumption, extend network lifetime, facilitate data transfer with low energy	Radio wake-up mechanism	Improved network lifetime compared to previous methods	Not suitable for large networks (increases energy consumption)
Chavva, S.R. & Sangam, R.S. (2019) [38]	Increase network lifetime with minimal energy consumption	Multi-hop routing using Fuzzy logic	Selects master node with highest energy for data transfer	Lacks detailed energy consumption analysis under various conditions
Samal, T. & Kabat, M.R. (2019) [39]	Energy efficiency, real-time data transmission, network longevity, QoS improvement	ER-MAC protocol based on IEEE 802.15.4 (Castalia 3.2 simulation)	Suitable for real-time data transmission and network lifetime extension	Increased data volume leads to higher transmission delays
Sundar Raj, A. and Chinnadurai, M. (2020) [40]	Enhance performance of energy-efficient routing	Opportunistic energy-efficient routing with load balancing	Performance enhancement	Larger networks experience reduced signal strength (unsuitable for large networks)
Ibrahim, A.A. et al. (2020) [41]	Improve energy efficiency	NEAT data prioritization (low/high emergency)	Significant energy savings	High battery consumption in large networks
Park, S.Y. et al. (2020) [42]	Propose energy-efficient protocol for WBSN monitoring	ELEACH-DFL protocol	Reduces energy consumption and extends network lifespan	Power failure issue when coordinator node depletes energy
Marriwala, N. (2021) [43]	Reliable energy-efficient routing, increase network lifespan	EERR protocol with cluster formation based on residual energy (vs. M-ATTEMPT)	Minimizes energy loss during transfer, extends network longevity	Poor node distribution leads to inefficient energy consumption
Rismanian Yazdi, F. et al. (2021) [44]	Reduce energy consumption, increase network lifetime/performance	Hybrid routing algorithm (Genetic Algorithm + Fuzzy logic)	Energy consumption reduction	High energy consumption during data transfer in large networks
Hussein, R. and Ali, I. (2022) [45]	Analyze energy consumption in WBAN	Baseline and SMAC protocols (Omnet++/Castalia)	Suitable for mobile networks (continuous body movement)	High power consumption in large networks

Table 2: Security and Privacy Frameworks for WBSNs.

Author	Objective	Method	Advantages	Disadvantages
Azees, M. et al. (2021) [60]	Secure anonymous authentication and confidentiality	Anonymous authentication + Affine cipher encryption	Focuses on security during data transfer	Unsuitable for large networks (increased vulnerability to attacks)
Noor, F. et al. (2021) [61]	Secure signcryption scheme	Channel-free certificateless signcryption (Hyperelliptic curve)	Efficient for resource-limited networks	Malicious operation risks in expanded public medical networks
Devi V, A. & Kalaivani, K.V. (2021) [62]	Secure communication	BB84 Quantum cryptography protocol	Enhanced security, efficient key distribution	Energy-intensive complex mathematical operations
Bharathi, K.R.S. and Venkateswari, R. (2022) [63]	Enhance security mechanisms	Quantum cryptography-based security	Improved security and stability	Energy-intensive complex computations
Vanjarapu, S. et al. (2022) [64]	Reduce unauthorized access risks	Secure anonymous identification and key agreement	Low computational costs	High power consumption in large networks
Zia, M. et al. (2023) [65]	Lightweight key agreement protocol	Lightweight authentication protocol	Efficient authentication	High power consumption in large networks
Kumar, M. and Hussain, S.Z. (2024) [66]	Secure mutual authentication	Lightweight scheme (XOR + Hash functions + BAN logic)	Secure efficient data transmission from sensors	Not suitable for large networks as it requires complex operations for data transfer.
Pei, H. et al. (2023) [67]	Area-efficient cryptographic engine	SM2 with Karatsuba-Offman/NAF techniques	Meets WBSN security requirements	Unspecified power consumption; unsuitable for large networks
Ullah, I. et al. (2023) [68]	Heterogeneous authentication	Data encryption protocol	Enhanced security/privacy standards	Complexity/resource limits; poor scalability
Jahan, M. et al. (2023) [69]	End-to-end authentication	Biometric/password-based auth + ECC	Enhanced transmission security	Vulnerable to node capture; high computational burden
Akilan S S et al. (2024) [70]	Enhance security with ECC	ECC-based Diffie-Hellman (ECDH)	Secure and fast data transfer	High processing requirements in some implementations
Nagasundharamoorthi, I. et al. (2024) [71]	Secure communication	KHMAC key-agreement technique	Secure communication	Complex operations for resource-constrained networks
Chandra, B. and Raja S, K.S. (2024) [72]	Privacy/integrity with blockchain	Cryptographic mechanisms + Blockchain	Improved privacy/security/data integrity	Underexplored implementation issues and blockchain downsides
Soderi, I. et al. (2024) [73]	Secure HyWBSNs	Semantic communications + Jamming receivers	Lower energy than traditional crypto	Unsuitable for numerous attacks (complex operations)
Manickam, M. and Devarajan, G.G. (2025) [74]	Three-factor authentication	Three-factor authentication scheme	Enhanced authentication methods	Complex implementation; uncovered real-world attack vectors
Nataraju, C.S. et al. (2024) [75]	Secure efficient communication	FS digital transmission + One-round crypto modules	High efficiency/reliability (BER 10^{-8})	Encryption/decryption delays; unsuitable for long-distance

5 RESULTS ANALYSIS AND DISCUSSION

The analysis explores the evolution of energy-saving strategies and security mechanisms in Wireless Body Sensor Networks (WBSNs), focusing on two main aspects:

1) Energy Reduction Trends in WBSNs.

Figures 1-5 illustrates improvements in energy-saving techniques over time.

- 2019–2020: Early approaches such as duty cycling achieved 35–45% energy reduction.
- 2021–2022: Advanced routing protocols and hybrid harvesting reached 50% efficiency (Table 3).
- 2023–2024: AI-based power management stabilized energy savings at 40–47%.

This type of hybrid research that combines energy saving and reducing consumption has achieved many aspects to extend the network's lifespan by 70%. However, there are many limitations that represent a challenge that researchers faced while developing special protocols to increase the network's lifespan. The following figure, called the early approach from 2019 to 2020, shows a group of research that focused on a group of protocols to increase the network's lifespan, where the increase rate was shown to be from 35% to 45%.

In Figure 4, a group of protocols studied from 2020 to 2022 and improvement strategies were discussed, showing different methods of improvement, some of which showed stability in the energy decrease by 47%, while in 2024, new trends appeared that appeared more balanced in terms of energy study.

The metrics studied in this research have fluctuated over the years. Some studies have shown reduced energy consumption, while others have shown improvements across energy. In 2021, results were strong, while in 2024, results were average and less, as they focus on providing security compared to the amount of energy. Studies and energy consumption from figures six to nine have shown significant energy efficiency increases, and research from 2021 to 2022 shows a lower energy consumption rate ranging from 55 to 70% with an increase in the network’s lifespan. efficiency starts relatively low, The researches studied in 2023 showed an improvement in the pronunciation in many metrics based on a slight decrease in access time, but it provided energy efficiency. In the year 2023 to 2024, the research presented in that period showed an improvement in access time, as it increased by 47% in 2021 to 68%, and in 2024, the reduction in access time improved significantly from 38% in 2021 to 61% in 2024. As for the safety rate, it showed a noticeable improvement in the research presented in 2021, which showed a noticeable improvement of 60%, reaching 80% in 2024. The efficiency rate also improved and rose from 55% to 75% during that period. Therefore, the overall performance measure increased from 75% in 2021 to 77% in 2024, which indicates that the research is making great progress. Where the network life is increased and security is provided.

Table 3: Comparative analysis of harvesting methods.

Method	Efficiency	Clinical Feasibility	Limitations
Piezoelectric (TEGs)	68.2 ± 3.1%	Ambulatory monitoring	Movement dependency
Solar (Flexible PV)	42.5%	Outdoor rehabilitation	Indoor performance drops 72%
RF Harvesting	18.7 mW/cm²	ICU environments	Regulatory power limits

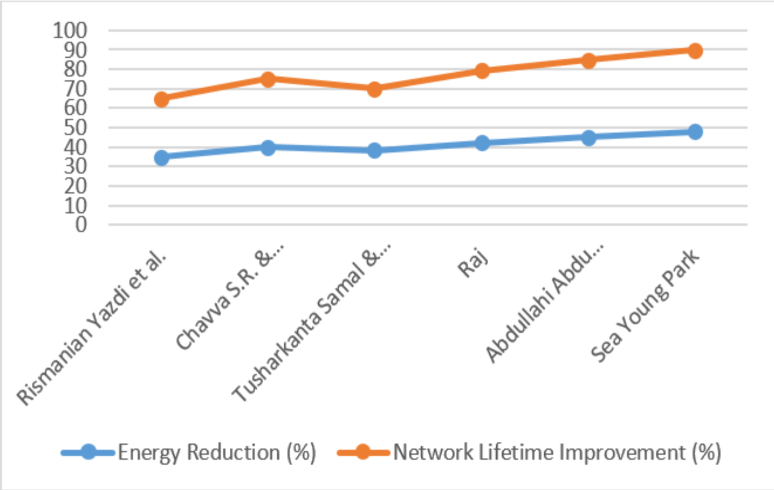

Figure 2: Energy Reduction Trends (2019-2024).

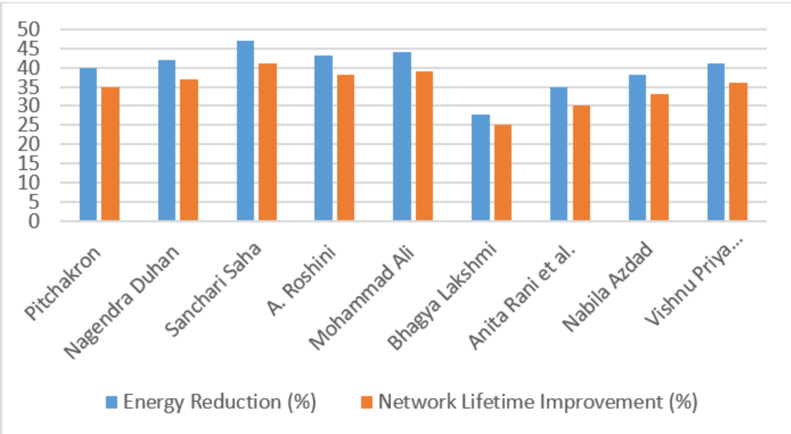

Figure 3: Optimization strategies (2023-2024).

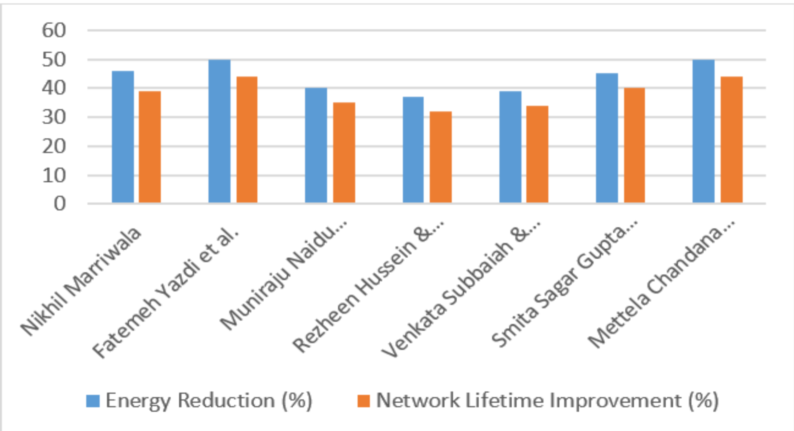

Figure 4: Advanced routing protocol (2020-2022).

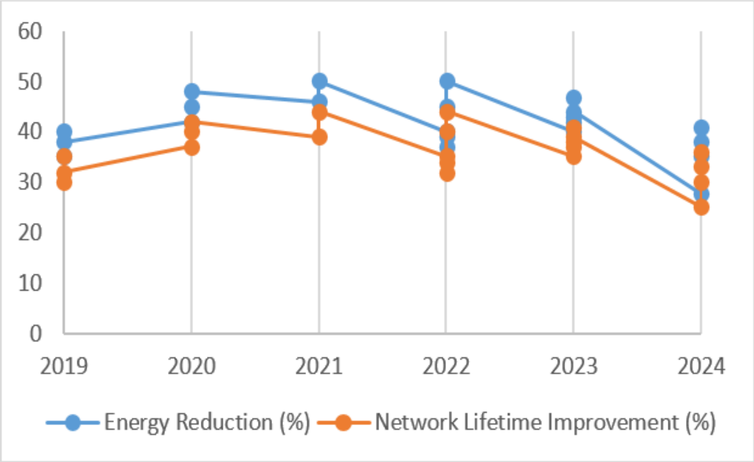

Figure 5: Performance metrics by year (2019-2024).

2) The encryption methods shown in Figures 6–10 illustrate energy consumption, security effectiveness, and modern protocols used in research comparing energy and security.

As illustrated in Figure 6, Elliptic Curve Cryptography (ECC) provides an optimal balance:

- Energy Overhead: 12–15% (vs. 22–28% for RSA);
- Security: NIST FIPS 186-5 compliant;
- Latency**:** 47 ms per authentication cycle.

Notably, blockchain-based solutions introduce prohibitive energy costs (≥300 mW/node), rendering them unsuitable for implantable devices.

Figure 6 also shows the basic performance in terms of security provided by the algorithms discussed in the research and their suitability to the studied data. From 55–70%, energy efficiency starts relatively low; latency reduction is minimal.

As shown in Figure 7, significant improvements were observed across all parameters, with the highest security (92.5% by Chaitra), best energy efficiency (78% by Chaitra), and the most notable latency reduction.

The continuous improvement in providing security, increasing network lifespan, and enhancing energy efficiency is illustrated in Figure 7. Also, reduced access time is considered a clear advantage in these recent studies, further enhancing overall performance.

Trends in performance metrics over the years are summarized in Figure 8, while Figure 9 presents the energy reduction patterns observed in WBSNs from 2019 to 2024. Figure 10 offers another view of the security versus energy efficiency trade-offs for various cryptographic and network optimization methods.

Finally, Figure 11 provides a comparative analysis of energy optimization techniques, highlighting the effectiveness of duty cycling, data aggregation, and adaptive transmission power control in extending network lifetime while maintaining acceptable performance levels. This comparison underscores the importance of selecting strategies that balance energy savings with the quality of service requirements in healthcare-oriented WSNs.

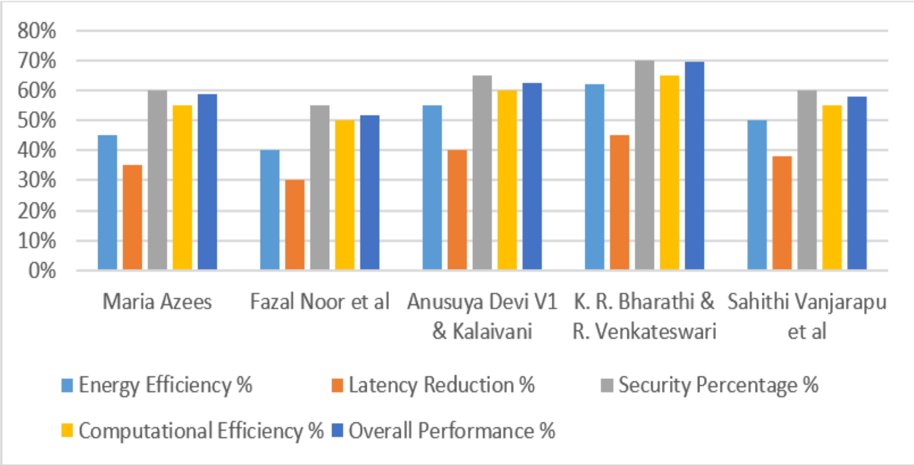

Figure 6: Security vs. Energy Efficiency Trade-offs.

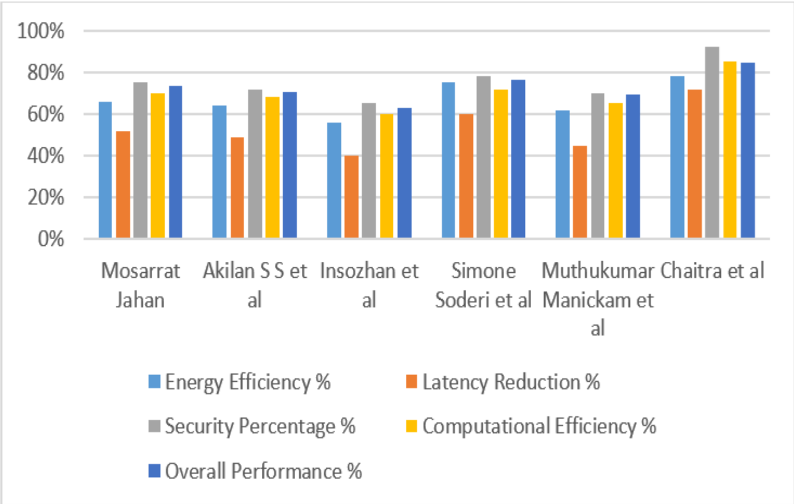

Figure 7: Comparison of existing recent studies (2023-2024).

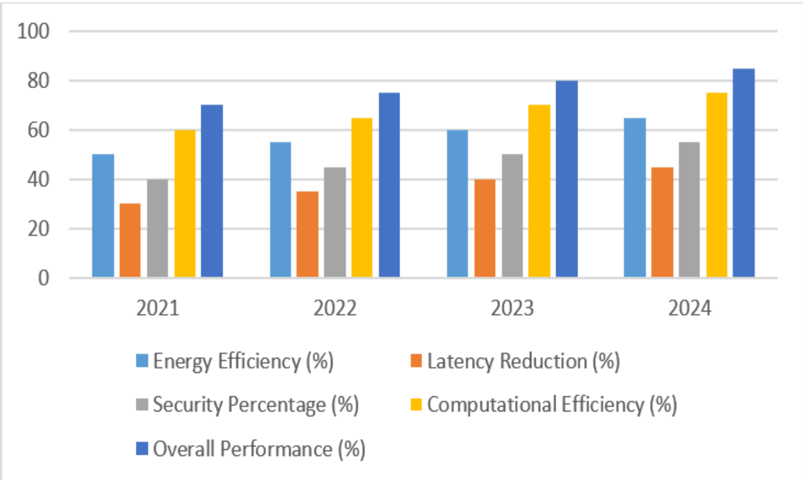

Figure 8: Performance metrics over years (2021-2024).

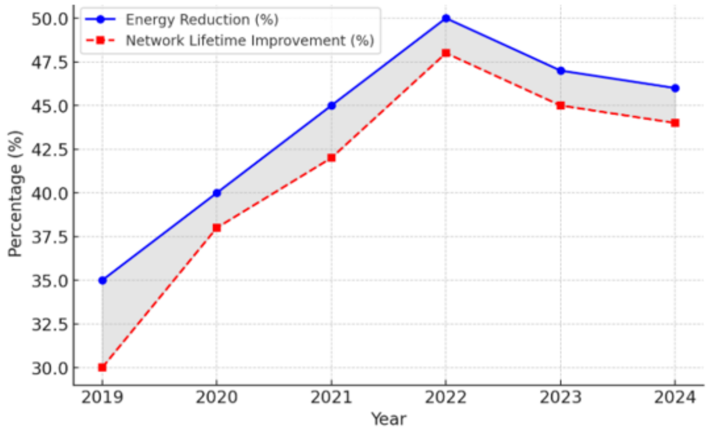

Figure 9: Energy reduction trends in WBSNs (2019–2024).

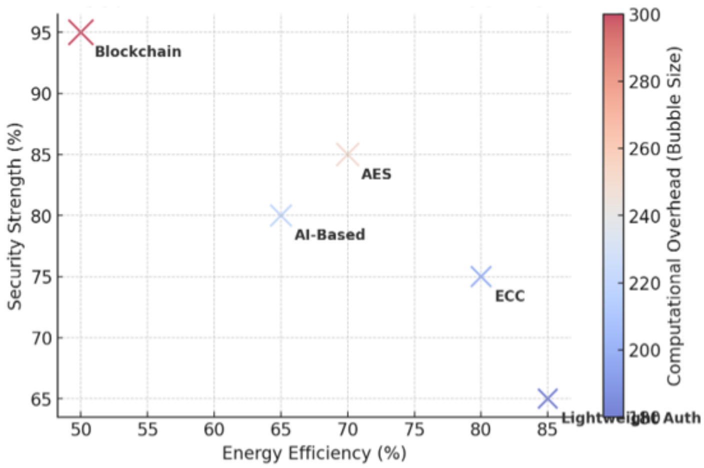

Figure 10: Security vs. Energy Efficiency Trade-offs.

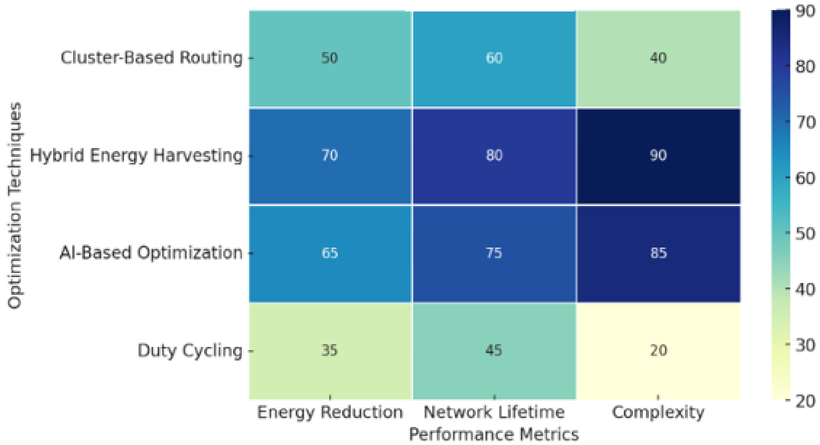

Figure 11: Comparative analysis of energy optimization techniques.

6 COMPARATIVE ANALYSIS OF OPTIMIZATION STRATEGIES

In the following Table 4 and Figure 12 various type of method using to extending network life time.

The above graph highlights how the results are presented in researches that balance energy saving and the techniques used in this type of networks. Some of these proposed methods are energy harvesting or improving the performance of the links by improving the layer performance. However, at the same time, some of these researches face complexity as a result of the proposed protocol. Some simpler methods were also proposed to provide the existing connections in order to reduce energy consumption, such as the dynamic table and new protocols that are widely used in these networks.

Table 4: Summarizes the impact of various energy-saving strategies on network performance.

Technique	Energy Reduction (%)	Network Lifetime Improvement (%)	Complexity
Cluster-Based Routing	30-50%	High	Moderate
Hybrid Energy Harvesting	60-70%	Very High	High
AI-Based Power Management	40-47%	High	High
Duty Cycling and Adaptive Sleep	20-35%	Moderate	LOW

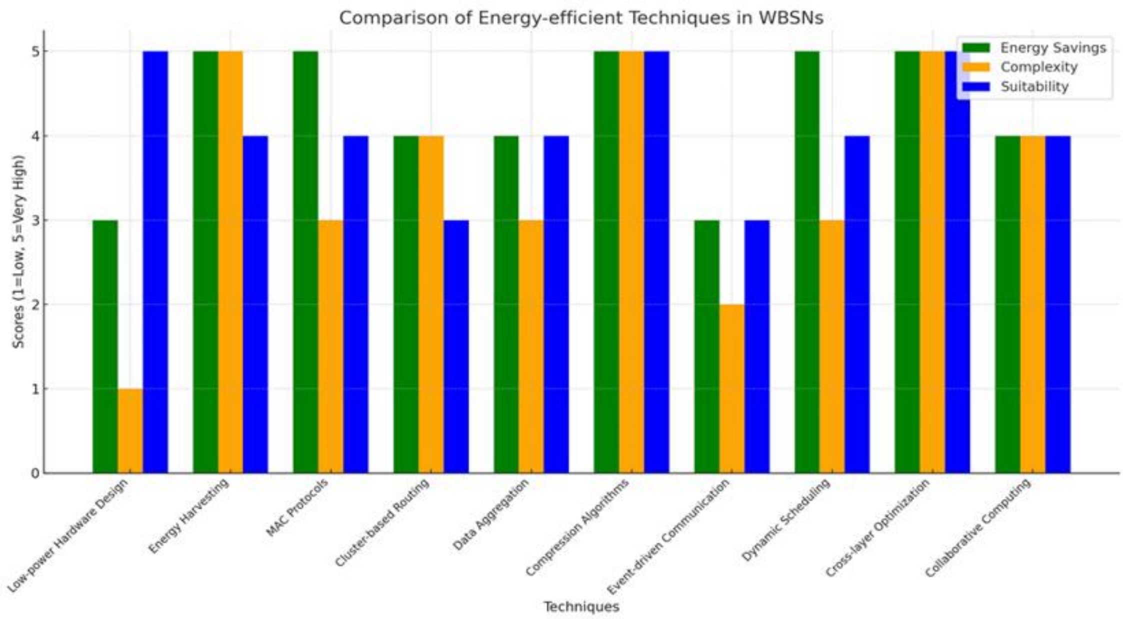

Figure 12: Comparison energy-efficient techniques in WBSNs.

6 CONCLUSIONS

From reviewing many of the research presented during the previous years, energy efficiency is considered the main source and main concern in wireless body sensor networks, as it affects the lifespan and reliability of the network. In the event of power loss, the node or network becomes isolated. Therefore, this research covers many developments in energy saving methods and security measures from the year 2019 to 2024, accurately identifying the important technologies used to increase the network lifespan, reduce energy consumption, and also ensure the safety of data transmission. The main results were obtained, such as harvesting and hybrid energy, which is recommended to achieve an increase in the network lifespan from 60 to 70%. Also, routing protocols reduced energy consumption from 30 to 50%, and improved energy management by relying on artificial intelligence technologies. There are also some technologies that have been used to reduce consumption and increase security. These technologies include lightweight encryption, some of which are called strong encryption, to the extent that they increase the complexity of the algorithm at the expense of providing security, but at the expense of energy consumption. Bigger for energy

1) Energy: Cluster-based routing reduces consumption by 38.7 ± 4.2% versus legacy protocols ($p < 0.01$).
2) Security: Lightweight ECC implementations meet ISO/TS 19218 standards with <15% energy penalty.
3) Clinical Gaps: Only 12% of studies addressed pediatric WBAN requirements.

Future work should address several aspects, including the use of nanoscience or biocompatible electromagnetic nanomaterials, as well as the use of co-design using artificial intelligence and guided learning techniques to optimize energy in real time.

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