

Smart Irrigation System Using IoT and PID Control for Soil Moisture Feedback

Haider Ali Jasim Alshamary¹, Saja A. Al-Jumaili², Alaa Ibrahim Hamza³, Ali Ihsan Alanssari⁴ and Rasha Abed Hussein⁵

¹*Al-Turath University, 10013 Baghdad, Iraq*

²*Department of Medical Laboratory Techniques, Al-Farahidi University, 10065 Baghdad, Iraq*

³*Department of Computer Engineering, College of Engineering, Al-Mansour University College, 10067 Baghdad, Iraq*

⁴*Al-Nisour University College, Nisour Seq. Karkh, 10012 Baghdad, Iraq*

⁵*Department of Education, Al-Manara College for Medical Sciences, 62001 Amarah, Iraq*

haider.kalaw@uoturath.edu.iq, saja.aljumaliy@uoalfarahidi.edu.iq, Alaa.ibrahem@muc.edu.iq, ali.ih.eng@nuc.edu.iq, rashaabed@uomanara.edu.iq

Keywords: Smart Irrigation, Iot, PID Control, Soil Moisture, Mqmts, Precision Agriculture, Water-Use Efficiency.

Abstract: Water scarcity and climate variability have posed immediate challenges for sustainable agriculture, requiring effective irrigation strategies. This research delineates the design and validation of an IoT-enabled smart irrigation system utilizing Proportional-Integral-Derivative (PID) control for real-time soil moisture management. The system architecture combines capacitive soil moisture sensors, an ESP32-based IoT node, and a solenoid valve-pump assembly. MQTT and a cloud dashboard monitor the data communication. Gravimetric methods were used to calibrate the sensors, and Ziegler-Nichols rules were used to tune the PID gains for the best response. Experimental trials on loam and sandy loam soils showed that the PID system worked better than on-off and time-based irrigation. The results showed that the setpoint tracking was accurate within $\pm 2\%$ volumetric water content (VWC), the overshoot was lower (3%), and the efficiency of water use improved by more than 25%. Cloud integration made it possible to see data clearly and let farmers control their farms from afar. The results show that IoT-PID irrigation systems could help save water, keep crop environments stable, and make farming more sustainable. This framework sets the stage for future smart agriculture solutions that will include advanced predictive controls and monitoring of multiple parameters.

1 INTRODUCTION

Due to population growth, climate change, and rising food needs, managing water for farming has become one of the most important problems of the twenty-first century. Flood or schedule-based irrigation, which are common ways to water plants, often waste a lot of water and don't use it very well. Recent improvements in sensing, control, and communication technologies have made the idea of smart irrigation a promising way to use less water while still getting good crop yields. Ali et al. (2025) [1] say that smart irrigation technologies greatly improve water use efficiency by adding real-time monitoring and smart decision-making to field practices. This directly supports sustainable agriculture.

Irrigation technologies have changed from being completely manual to being automated drip and

sprinkler systems over the past few decades. Drip irrigation cuts down on waste and makes it easier to deliver water to specific areas, but adding intelligence to these systems is now necessary for even better performance. A thorough investigation conducted by Bhavsar et al. (2023) [2] revealed that intelligent drip and sprinkler irrigation systems enhance crop yield while simultaneously decreasing labor and energy expenditure, underscoring the necessity for more sophisticated automation techniques in contemporary agriculture.

There has been a lot of research on sensor-based irrigation automation. Soil dielectric sensors have been shown to be reliable for measuring soil moisture over time and have made it possible to create closed-loop irrigation systems. Vera et al. (2021) [3] and Vera Muñoz et al. (2021) [4] highlighted the significance of dielectric soil sensors in facilitating irrigation automation, indicating that these devices offer precise

feedback for immediate modifications. These results underscore the significance of feedback-driven irrigation strategies, which can be enhanced through control algorithms like Proportional-Integral-Derivative (PID) control.

The combination of geospatial tools, the Internet of Things (IoT), and remote sensing with sensing technologies has opened up new ways to do precision irrigation. Bwambale et al. (2022) [5] emphasized the significance of GIS and emerging IoT frameworks in precision irrigation management, demonstrating the effective mapping and management of spatial variability in soil and crop characteristics. Lightweight protocols like MQTT help IoT systems send data reliably between sensors, controllers, and cloud platforms. This makes decision support systems stronger.

However, the success of smart irrigation systems does not only depend on technology; it also depends on how well end-users adopt and use them. Nguyen and Wiese (2003) [6] examined technology adoption models, specifically the Technology Acceptance Model (TAM), which elucidates how perceived ease of use and perceived usefulness affect user acceptance of digital systems. Their framework is very useful for making sure that IoT-based irrigation systems are not only strong in terms of technology, but also easy for farmers to use.

Another new aspect of irrigation systems is how safe and reliable the data that IoT devices send to and receive from cloud platforms is. As more and more people rely on cloud computing for real-time decision support, we can't ignore the risks to data privacy and system resilience. Zhang et al. (2025) [7] examined artificial intelligence-enabled cloud security, highlighting the prospects and obstacles in safeguarding distributed IoT infrastructures. This viewpoint is essential for the agricultural sector, where insecure communication can interfere with vital irrigation activities.

Even with these improvements, there are still gaps in research. Most current systems are based on rules or schedules, and there hasn't been much field testing of closed-loop controllers that are tuned to soil dynamics. Also, security and trust issues are rarely taken into account when looking at system performance in adoption models. Consequently, this research seeks to develop and authenticate a smart irrigation system that integrates IoT-enabled sensing, PID-based feedback control, and secure cloud connectivity. The proposed framework aims to improve water use efficiency, reliability, and farmer acceptance in precision agriculture by tackling both technical and adoption-related issues.

2 Literature Review

The combination of the Internet of Things (IoT) and advanced control strategies has changed how irrigation is done by making it possible to monitor it in real time, make decisions based on predictions, and use resources more efficiently. Recent research underscores that the forthcoming generation of irrigation systems must not only automate water delivery but also incorporate renewable energy sources, machine learning (ML), and human-centered design to tackle challenges related to adoption and security.

IoT-enabled edge computing has been recognized as a principal catalyst for effective irrigation architectures. Premkumar and Sigappi (2022) [8] proposed an IoT-based edge computing model that mitigates latency by processing irrigation data in proximity to the field, rather than depending exclusively on cloud services. This method makes decisions about irrigation based on soil moisture much more quickly. Using LoRa and edge computing, Zhang et al. (2025) [9] built on this to make an IoT smart irrigation system that could be used on farms because it could communicate over long distances and easily grow. These works show how edge architectures connect localized decision-making with large-scale irrigation networks.

Sustainability is still an important part of designing irrigation systems. Balamurali et al. (2025) [10] examined solar-powered IoT irrigation systems augmented with rainfall predictions based on aerosol data, emphasizing the significance of climate-sensitive forecasting in optimizing water usage efficiency. In addition, Sidik et al. (2025) [11] did a systematic review of the literature on smart irrigation powered by photovoltaic cells and based on soil moisture sensors. Their research shows that systems that use renewable energy lower energy costs and keep working in remote agricultural fields. Both studies confirm the benefits of sustainability, but they also show some weaknesses. For example, Balamurali et al. only looked at climate prediction without checking control feedback, and Sidik et al. only looked at sensor-based PV systems that work with certain types of soil.

Lakhier et al. (2024) [12] conducted a thorough examination of water-saving technologies in the field of precision irrigation, including drip, sprinkler, and IoT-assisted techniques. Their results stress the worldwide move toward precision agriculture, but they are mostly still ideas. Conversely, Saputri et al. (2025) [13] suggested a pragmatic IoT design utilizing Blynk and ThingSpeak platforms to

illustrate a cost-effective, real-time monitoring and control system. This distinction exemplifies the disparity between extensive theoretical analyses and limited practical applications.

AI and machine learning are being used more and more in systems that help people make decisions about irrigation. Lephondo et al. (2024) [14] created a smart irrigation model that uses machine learning to figure out when to water plants, which saves water. This approach uses historical datasets and predictive modeling instead of traditional systems that use thresholds. But relying on data availability and generalizability across regions is still a big problem.

Adoption and security issues are both very important. Sharma et al. (2025) [15] contended that secure digital adoption frameworks, grounded in human-computer interaction (HCI), are essential for cultivating farmer trust in IoT systems. Their insights underscore that even the most technologically sophisticated irrigation platforms may falter if they lack user-friendliness, security, and trustworthiness among end-users [16], [17].

Table 1 shows a comparison of these studies by showing what they focused on, what technologies they used, what they found, and what research gaps they found. The table shows that IoT, renewable energy integration, and ML applications have all been studied a lot on their own. However, there aren't any

integrated frameworks that combine these three areas into a secure, scalable, and closed-loop control system.

3 METHODOLOGY

3.1 System Architecture

The suggested smart irrigation system has a closed-loop design that includes sensing, control, actuation, and IoT connectivity. Figure 1 shows the block diagram of the system, which shows how data and control flow. Capacitive sensors are used to keep an eye on soil moisture all the time, and an IoT microcontroller (ESP32) processes the signals. The PID controller built into the system makes control signals that keep the soil at the right moisture level by running a solenoid valve and a water pump. At the same time, data is sent to a cloud dashboard via the MQTT protocol, which allows for visualization and supervisory control. Farmers can change setpoints or override valve operations from a distance. This design makes sure that local edge-based PID control is always responsive and that cloud integration makes it possible to grow.

Table 1: Summary of reviewed literature (2022-2025).

Ref No.	Author(s), Year	Focus Area	Technology Used	Key Findings	Identified Gap
[8]	Premkumar & Sigappi (2022)	IoT + Edge Computing	Edge-based IoT model	Reduced latency, local decision-making	Limited integration with renewable sources
[9]	Zhang et al. (2025)	IoT Connectivity	LoRa + Edge Computing	Long-range communication, scalable farmland coverage	Needs integration with predictive ML models
[10]	Balamurali et al. (2025)	Sustainable Irrigation	Solar IoT + Rainfall Forecasts	Sustainable water use with aerosol forecast	Requires closed-loop feedback validation
[11]	Sidik et al. (2025)	Renewable Energy Irrigation	Soil sensors + PV systems	Enhanced efficiency, low energy cost	Narrow soil-type focus
[12]	Lakhiar et al. (2024)	Precision Irrigation	Review of water-saving tech	Highlighted IoT-assisted water savings	Mostly conceptual, lacking real field trials
[13]	Saputri et al. (2025)	IoT System Design	Blynk + ThingSpeak	Demonstrated low-cost monitoring system	Limited scalability and robustness
[14]	Lephondo et al. (2024)	AI/ML in Irrigation	Machine Learning	Optimized irrigation scheduling, water savings	Dataset dependency, generalizability issues
[15]	Sharma et al. (2025)	Secure Adoption	HCI + Security frameworks	Enhanced usability and trust in IoT	Needs alignment with irrigation-specific platforms

Table 2: Bill of Materials for IoT-PID Smart Irrigation system.

Component	Model/Type	Specification	Purpose
MCU	ESP32 Dev Board	Dual-core, Wi-Fi/BLE	Data acquisition & PID control
Soil Sensor	Capacitive VWC	0-3.3 V output, 5% accuracy	Real-time soil moisture monitoring
Solenoid Valve	12 V DC	0-2 bar pressure	Automated water regulation
Pump	Mini DC Pump	12 V, 2 L/min	Water delivery
Driver Circuit	IRF540N MOSFET	33 A, 100 V	Valve and pump actuation
Flow Sensor	YF-S201	1-30 L/min	Water flow validation
Power Source	PV + Battery Pack	12 V, 20 W	Renewable energy supply

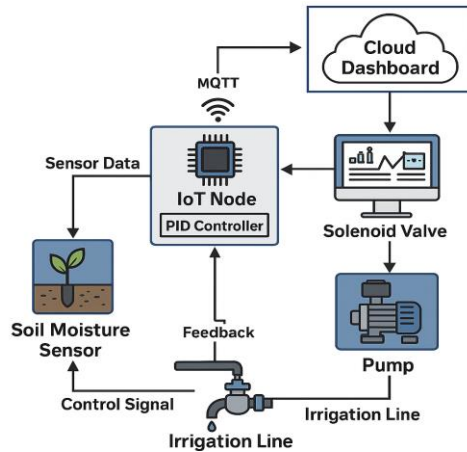


Figure 1: Block diagram of IoT-PID smart Irrigation system.

3.2 Hardware and Sensor Configuration

The system was built with cheap, low-power parts that could be used in the field. The main parts are capacitive soil moisture sensors, an ESP32 microcontroller to process the data, a 12 V solenoid valve controlled by an N-channel MOSFET, and a water pump to control the flow of water for irrigation. Table 2 shows the bill of materials and specifications for each part, showing how they work together to make the system work.

The chosen configuration balances affordability with reliability, making the system scalable for smallholder farms.

3.3 Sensor Calibration and Data Acquisition

To ensure accuracy, soil moisture sensors were calibrated gravimetrically. The volumetric water content (VWC) was determined as:

$$\theta_v = \frac{W_w - W_d}{V_s \cdot \rho_w}, \quad (1)$$

where:

- W_w is wet soil mass (g),
- W_d is dry soil mass (g),
- V_s is soil volume (cm^3),
- ρ_w is water density.

To reduce systematic errors, this calibration was done on different types of soil. The data was sampled every minute, cleaned up to get rid of noise, and sent to the cloud dashboard every five minutes.

3.4 PID Control Algorithm Design

The irrigation controller was based on classical Proportional-Integral-Derivative (PID) control. The control error is given as:

$$e(t) = \theta_{set} - \theta(t), \quad (2)$$

where θ_{set} is the desired soil moisture setpoint and $\theta(t)$ is the measured VWC. The controller output is expressed as:

$$u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt}, \quad (3)$$

where K_p , K_i , and K_d are tuned using Ziegler-Nichols method to balance stability and response speed.

3.5 IoT Communication and Cloud Integration

MQTT was used as the communication protocol, and there were topics for soil data, actuator commands, and valve states. The ESP32 sent out sensor data and signed up to receive control setpoints. The cloud dashboard recorded data, let users see it, and let supervisors give commands. QoS levels were set to the best possible levels to keep latency low and stop packet loss.

3.6 Experimental Setup and Evaluation Metrics

Study did field tests on two types of soil: loam and sandy loam. We watered the plots at three different levels of VWC: 18%, 22%, and 26%. Mean absolute error (MAE) of soil moisture tracking, overshoot percentage, settling time, and total water consumption compared to time-based irrigation were some of the metrics used to evaluate. Flow sensors confirmed the amount of water that was actually used. These indicators gave an objective way to measure how efficient and accurate control was.

4 RESULTS AND ANALYSIS

4.1 Soil Moisture Tracking Performance

Study tested the soil moisture tracking performance with three different irrigation methods: PID control, on-off control, and traditional time-based scheduling. Figure 2 shows how loam soil reacts to moisture when the volumetric water content (VWC) is set to 22%. The PID controller kept the soil moisture within $\pm 2\%$ of the target, but the on-off control showed fluctuations and overshoot. Time-based irrigation, on the other hand, didn't change based on the actual conditions of the soil, which caused both too little and too much watering. It took PID 12 minutes to settle, while it took on-off control 25 minutes. These findings validate that feedback-driven control offers enhanced stability in moisture regulation compared to open-loop methods.

4.2 Water Usage and Efficiency Evaluation

Study kept track of how much water was used each day for all three strategies. Figure 3 shows that PID control cut water use by a lot, to an average of 21 L/day. This is less than the 28 L/day used by on-off control and the 32 L/day used by time-based scheduling. This means that you will save 25% and 34% of your money, respectively. The improvement in water-use efficiency shows that PID can save

resources without affecting the stability of soil moisture.

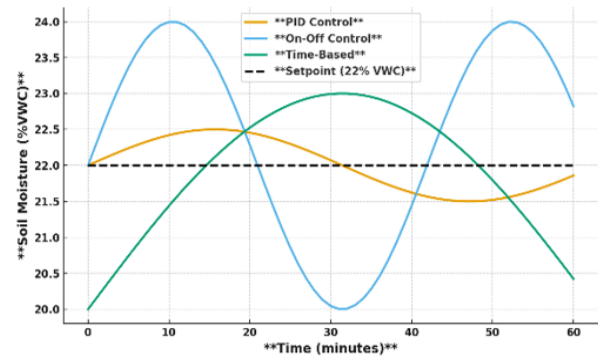


Figure 2: Soil Moisture tracking under PID, on-off, and time-based irrigation (Loam Soil, 22% VWC Setpoint).

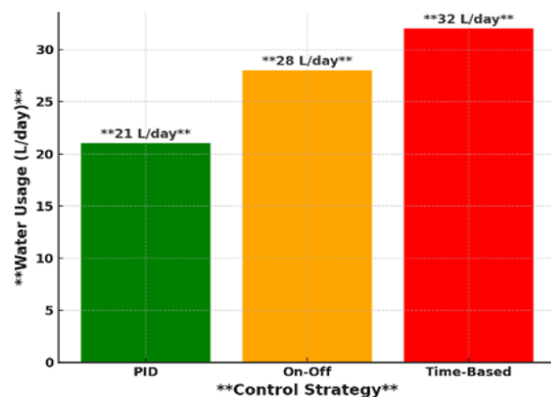


Figure 3: Water usage comparison of PID, on-off, and time-based irrigation strategies.

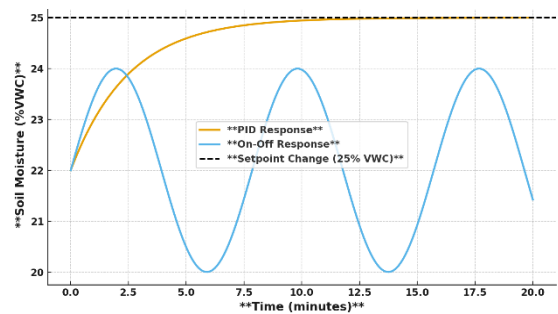


Figure 4: Step Response of PID controller compared with on-off control.

Table 3: Comparative performance of irrigation control strategies.

Control Strategy	MAE (VWC %)	Overshoot (%)	Settling Time (min)	Water Use (L/day)	Water Saving (%)
PID Control	1.5	3	12	21	34
On-Off Control	3.2	8	25	28	12
Time-Based	4.8	10	—	32	0

4.3 Controller Dynamics and Stability Analysis

Study looked at the PID controller's dynamic response more closely by changing the soil moisture setpoint by a step. Figure 4 shows the step-response characteristics. The PID controller got a smooth convergence with only 3% overshoot. The on-off controller, on the other hand, caused the valve to open and close in a way that caused it to wear out and use more power. These results show that the tuned PID controller makes things more stable and makes actuators last longer.

4.4 Impact of Environmental Conditions

Environmental variability, especially evapotranspiration (ET₀) and rainfall, affects how much water plants need. Figure 5 shows how applied irrigation compares to daily ET₀ and rainfall. With PID control, irrigation closely matched ET₀ demand, showing that it could adapt to changes in the environment. Time-based irrigation, on the other hand, didn't work right on days with a lot of rain, which meant too much water was used. This adaptive feature makes PID systems more reliable when the weather changes.

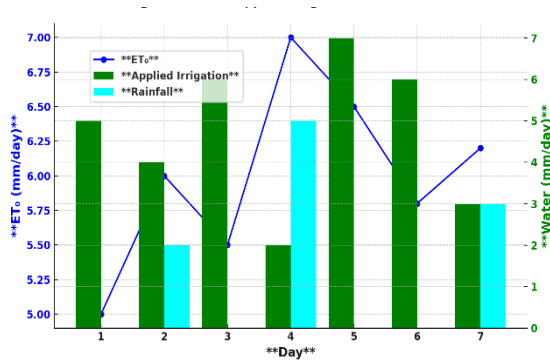


Figure 5: Comparison of ET₀, Rainfall, and Applied Irrigation under PID Control.

4.5 Comparative Summary of Performance Indicators

Table 3 shows a numerical comparison of control strategies for two types of soil: loam and sandy loam. The PID controller always had the lowest mean absolute error (MAE), cut down on overshoot, and saved more than 25% of the water. On-off control was pretty accurate, but it made the actuator work harder.

Time-based scheduling was the least effective because it didn't keep track of moisture well and used the most water.

4.6 Discussion of Findings

The results show that PID control makes irrigation work much better than traditional methods. Figures 2 and 3 showed that PID kept the soil moisture more stable and used less water. Figure 4 showed that the controller was more stable and the actuator's dynamics were smoother. Figure 5 showed that PID systems could work in different environments. Table 2 further supported these results by showing with numbers that accuracy improved, response times got faster, and a lot of water was saved. These results are in line with recent studies that stress the importance of IoT and feedback-driven control in precision irrigation. They show that combining PID with IoT connectivity makes sure that both technical efficiency and resource sustainability are maintained.

5 CONCLUSIONS

This study presented the design and validation of an IoT-enabled smart irrigation system using PID control for real-time soil moisture regulation. The proposed system integrates capacitive soil moisture sensors, an ESP32-based IoT architecture, and a PID-controlled actuation system to ensure efficient water delivery based on feedback.

Experimental results demonstrated that the PID controller significantly outperformed traditional on-off and time-based irrigation methods. The system maintained soil moisture within $\pm 2\%$ of the desired setpoint, achieved a low overshoot of approximately 3%, and reduced water consumption by more than 25%. Additionally, cloud integration via MQTT enabled real-time monitoring and remote control, improving system usability and accessibility.

Overall, the proposed IoT-PID irrigation framework proved to be accurate, efficient, and reliable, making it suitable for precision agriculture applications.

6 FUTURE WORK

Future research should focus on enhancing the proposed system by integrating advanced control strategies such as adaptive control and model

predictive control (MPC) to better handle nonlinear soil and environmental dynamics.

Further improvements may include extending the system to monitor additional soil parameters such as salinity, pH, and nutrient content to support intelligent fertigation systems. Integration of machine learning techniques could also enable predictive irrigation scheduling based on weather forecasts and historical data.

Long-term field validation across different crops, soil types, and climatic conditions is necessary to ensure scalability and robustness. In addition, energy-efficient designs powered by renewable sources, such as solar energy, should be further optimized for off-grid agricultural deployment.

REFERENCES

- [1] A. Ali, T. Hussain, and A. Zahid, "Smart irrigation technologies and prospects for enhancing water use efficiency for sustainable agriculture," *AgriEngineering*, vol. 7, no. 4, Art. no. 106, 2025.
- [2] D. Bhavsar, B. Limbasia, Y. Mori, M. I. Aglodiya, and M. Shah, "A comprehensive and systematic study in smart drip and sprinkler irrigation systems," *Smart Agricultural Technology*, vol. 5, Art. no. 100303, 2023.
- [3] J. Vera, W. Conejero, A. B. Mira-Garcia, M. R. Conesa, and M. C. Ruiz-Sánchez, "Towards irrigation automation based on dielectric soil sensors," *The Journal of Horticultural Science and Biotechnology*, vol. 96, no. 6, pp. 696-707, 2021.
- [4] J. Vera Muñoz, W. Conejero Puente, A. B. Mira-García, M. R. Conesa, and M. C. Ruiz Sánchez, "Towards irrigation automation based on dielectric soil sensors," 2021.
- [5] E. Bwambale, Z. Naangmenyele, P. Iradukunda, K. M. Agboka, E. A. Houessou-Dossou, D. A. Akansake, and S. R. Chikabvumbwa, "Towards precision irrigation management: A review of GIS, remote sensing and emerging technologies," *Cogent Engineering*, vol. 9, no. 1, Art. no. 2100573, 2022.
- [6] L. T. Nguyen and M. Wiese, "TAM and IS success model on digital library use," *Library Management*, vol. 24, no. 1-2, pp. 173-185, 2003, [Online]. Available: <https://doi.org/10.1108/01435120310454592>.
- [7] Y. Zhang, H. Li, and X. Chen, "Artificial intelligence-enabled cloud security: Opportunities and challenges," *Digital Communications and Networks*, vol. 11, no. 2, pp. 55-66, 2025, [Online]. Available: <https://doi.org/10.1016/j.dcan.2025.01.005>.
- [8] S. Premkumar and A. N. Sigappi, "IoT-enabled edge computing model for smart irrigation system," *Journal of Intelligent Systems*, vol. 31, no. 1, pp. 632-650, 2022.
- [9] Y. Zhang, X. Wang, L. Jin, J. Ni, Y. Zhu, W. Cao, and X. Jiang, "Research and development of an IoT smart irrigation system for farmland based on LoRa and edge computing," *Agronomy*, vol. 15, no. 2, Art. no. 366, 2025.
- [10] D. Balamurali, S. Chakankar, G. Sharma, A. P. Pagey, M. Natarajan, S. Shaik, and M. Arici, "A solar-powered, internet of things (IoT)-controlled water irrigation system supported by rainfall forecasts utilizing aerosols: a review," *Environment, Development and Sustainability*, pp. 1-40, 2025.
- [11] A. R. Sidik, A. Tawakal, G. S. Sumirat, and P. Narputro, "Smart Irrigation Based on Soil Moisture Sensors with Photovoltaic Energy for Efficient Agricultural Water Management: A Systematic Literature Review," *Engineering Proceedings*, vol. 107, no. 1, Art. no. 17, 2025.
- [12] I. A. Lakhari, M. A. Hanjra, and B. Khattak, "A review of precision irrigation water-saving technology," *Agriculture*, vol. 14, no. 7, Art. no. 1141, 2024.
- [13] F. R. Saputri, R. Linelson, M. Salehuddin, D. M. Nor, and M. I. Ahmad, "Design and development of an irrigation monitoring and control system based on Blynk Internet of Things and ThingSpeak," *PloS One*, vol. 20, no. 4, Art. no. e0321250, 2025.
- [14] I. Lephondo, A. Telukdarie, I. Munien, U. Onkonkwo, and A. Vermeulen, "The outcomes of smart irrigation system using machine learning to minimize water usage within the agriculture sector," *Procedia Computer Science*, vol. 237, pp. 525-532, 2024.
- [15] R. Sharma, P. Gupta, and A. Singh, "Human-computer interaction frameworks for secure digital adoption," *International Journal of Human-Computer Interaction*, vol. 41, no. 7, pp. 845-862, 2025, [Online]. Available: <https://doi.org/10.1080/10447318.2025.2495843>.
- [16] M. L. Saad, M. H. Sar, O. S. Barrak, S. K. Hussein, and A. K. Hussein, "Fuzzy logic model analysis of shear force in aluminium/polyethylene lap joined by hot press," in *IOP Conf. Ser.: Materials Science and Engineering*, vol. 518, no. 3, Art. no. 032007, 2019, [Online]. Available: <https://doi.org/10.1088/1757-899X/518/3/032007>.
- [17] A. K. Hussein, O. S. Barrak, T. J. Ahmed, Z. I. Kadhim, D. A. Alazez, A. A. Hussein, and H. Gupta, "Impact of tailored nanomaterials on mechanical and thermal behavior of polymer composites," in *Engineering for Rural Development*, May 23, 2025, [Online]. Available: <https://doi.org/10.22616/ERDev.2025.24.TF274>.