Smart Water Management in Agriculture Using IoT and Soil Moisture Sensors

Firman Arifin[1], Depandi Enda[2]

[1]Department of Electronic Engineering, Politeknik Elektronika Negeri Surabaya (PENS) Surabaya, East Java, Indonesia.
E-mail: firman@pens.ac.id
[2]Departement of Informatics, Politeknik Negeri Bengkalis, Bengkalis, Indonesia.
E-mail: depandienda@polbeng.ac.id

Article Info

Article History:

Received Dec 19, 2025
Revised Jan 15, 2026
Accepted Feb 12, 2026

Keywords:

Internet of Things (IoT)
Smart Water Management
Soil Moisture Sensors
Smart Irrigation System
Precision Agriculture

ABSTRACT

Advances in the Internet of Things (IoT) are helping to make water management smarter and optimizing consumption in the smart agriculture industry. Efficient water management is a critical challenge in modern agriculture due to increasing water scarcity and the inefficiency of conventional irrigation practices. This paper presents a Smart Water Management System for agriculture using the Internet of Things (IoT) and soil moisture sensors, aimed at optimizing irrigation by delivering water based on real-time soil conditions. The proposed system integrates soil moisture sensors with a microcontroller and wireless communication module to continuously monitor soil moisture levels and transmit data to a cloud-based IoT platform. Based on predefined threshold values, the system automatically controls irrigation through actuators such as water pumps or solenoid valves, thereby minimizing human intervention. Real-time monitoring and remote access are enabled through a web or mobile application, allowing farmers to make informed decisions. Experimental results demonstrate that the proposed system significantly reduces water consumption while maintaining optimal soil moisture levels for crop growth. The system offers a low-cost, scalable, and energy-efficient solution that enhances water-use efficiency and supports sustainable agricultural practices.

Corresponding Author:

Firman Arifin,
Department of Electronic Engineering,
Politeknik Elektronika Negeri Surabaya (PENS), Surabaya, East Java, Indonesia.
E-mail: firman@pens.ac.id

1. INTRODUCTION

Agriculture represents one of the largest consumers of freshwater resources globally, accounting for a substantial share of total water withdrawals. Growing population demands [1], increasing climate variability, and the progressive depletion of available water reserves have intensified the need for efficient water management strategies in the agricultural sector. Conventional irrigation methods, typically based on fixed scheduling or manual decision-making, frequently lead to over-irrigation, uneven water distribution, and suboptimal crop yields. These limitations underscore the necessity for intelligent and automated irrigation systems capable of adjusting water application according to real-time field conditions.

Wireless Sensor Networks (WSNs), a foundational component of the Internet of Things (IoT), have experienced significant development in recent years. One of the key advantages of WSNs lies in their ability to establish distributed networks of interconnected sensor nodes that collect and transmit environmental data from monitored areas through wireless communication links. Information gathered by multiple nodes is relayed to a gateway and subsequently integrated into broader communication infrastructures [2], such as wireless Ethernet networks. Owing to these capabilities, WSNs have been successfully applied across various domains, including environmental surveillance, forest fire detection, smart cities, healthcare systems, military operations, water quality monitoring, and asset tracking. Their flexibility and scalability make them particularly suitable for agricultural applications.

Among emerging IoT communication technologies, Long Range (LoRa) Low-Power Wide-Area Network (LPWAN) has gained considerable attention [3]. LoRa offers several advantages, including extended communication range, low energy consumption [4], and straightforward deployment. These features make it well suited for large-scale agricultural environments, where sensor nodes may be distributed across wide geographic areas and must operate with limited power resources.

In agricultural contexts, continuous environmental monitoring is essential for maintaining optimal crop growth conditions. WSN-based systems can collect real-time measurements of parameters such as soil moisture, temperature, humidity, and rainfall, enabling more accurate estimation of crop water requirements. Beyond basic environmental monitoring, advanced systems are being developed to regulate irrigation levels and maintain temperature control within controlled agricultural environments. By leveraging IoT technologies [5], smart irrigation systems can integrate sensor data, communication networks, and automated control mechanisms to improve water-use efficiency and crop productivity.

The rapid growth of IoT has been driven by several enabling factors, including the availability of affordable sensing devices, low-power wireless communication technologies, cloud-based storage and processing platforms, high-performance computing resources [6], and advanced data analytics techniques. Together, these components facilitate the management and analysis of large volumes of heterogeneous data, supporting intelligent decision-making in smart agriculture applications.

Despite these advancements, several challenges continue to hinder the large-scale adoption of IoT-based precision irrigation systems. First, the development of IoT software for agricultural applications is not yet fully automated [7], often requiring significant customization and technical expertise. Second, comprehensive IoT platforms capable of seamlessly integrating sensing technologies, big data analytics, cloud and fog computing, and automated control mechanisms are still under development. Third, the integration of diverse and heterogeneous sensor technologies demands standardized communication protocols and data models to ensure interoperability and system reliability.

Addressing these challenges is essential to unlocking the full potential of IoT-enabled smart irrigation systems and achieving sustainable water management in agriculture [8].

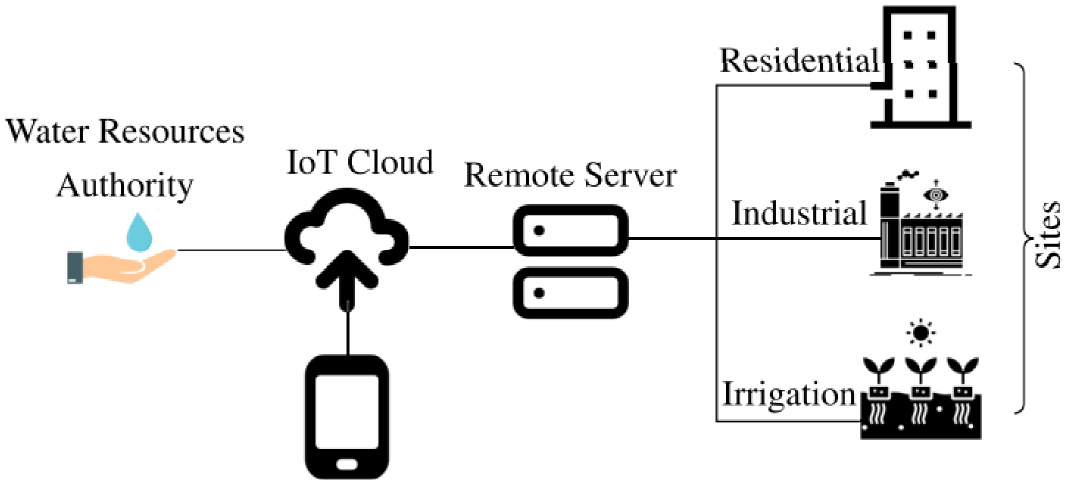

Figure 1. Illustration of an IoT-based water management system

1.1 System Architecture for Water Resource Monitoring

The proposed water resource monitoring and management framework is designed to support agricultural, industrial, and residential applications through an integrated IoT infrastructure. The architecture incorporates multiple types of sensors deployed in the field and interconnected through Wireless Sensor Networks (WSNs). These sensor nodes collect environmental and water-related parameters and transmit the data to a centralized IoT cloud platform. The cloud infrastructure enables storage, processing, visualization, and remote access, facilitating intelligent decision-making and efficient water utilization across diverse application domains.

1.2 Problem Statement

Although modern irrigation technologies are available, many agricultural systems continue to experience inefficient water usage due to the absence of real-time monitoring and automated control. Traditional irrigation practices typically operate on fixed schedules or manual intervention without considering actual soil moisture variations. This often results in excessive watering or insufficient irrigation, both of which negatively impact crop growth and lead to unnecessary water loss.

Manual irrigation management is labor-intensive and susceptible to human error, making it unsuitable for large-scale or precision farming applications. Furthermore, many existing irrigation solutions lack integration with cloud platforms, limiting their capability for continuous monitoring, historical analysis, and data-driven decision-making.

There is therefore a clear need for a cost-effective, scalable, and intelligent irrigation system capable of continuously monitoring soil moisture conditions, automatically regulating water supply based on real-time data, and providing remote access for farmers. An IoT-enabled water management system that integrates soil moisture sensing, automated threshold-based control, and cloud connectivity can significantly improve irrigation efficiency, reduce operational costs, and promote sustainable agricultural practices.

1.3 Main Contributions

This study offers several key contributions to IoT-driven precision irrigation systems:

1. A scalable and modular IoT-based architecture is developed for real-time soil moisture monitoring and automated irrigation control. The system integrates sensor nodes, a microcontroller-based controller, wireless communication modules, and cloud services.
2. A threshold-based irrigation control algorithm is designed and implemented to dynamically regulate water application. The algorithm continuously analyzes preprocessed soil moisture data to maintain optimal moisture levels while preventing over-irrigation.
3. Robust data preprocessing and feature extraction techniques are incorporated to enhance sensor data reliability and support accurate decision-making.
4. The proposed system is experimentally evaluated under real field conditions, with detailed analysis of soil moisture regulation, water consumption, and crop health indicators.
5. The framework demonstrates stable operation, efficiency, and scalability, confirming its suitability for large-scale smart irrigation deployment.

1.4 Paper Organization

The remainder of this paper is structured as follows: Section 2 reviews related work on IoT-based irrigation and smart water management systems. Section 3 describes the materials and methods, including system architecture, data acquisition, preprocessing, feature extraction, and control strategies. Section 4 presents the system implementation and discusses experimental findings supported by analytical evaluation. Section 5 concludes the paper and highlights the significance and future potential of the proposed approach.

2. LITERATURE REVIEW

Recent advancements in precision agriculture increasingly emphasize the integration of Internet of Things (IoT) technologies with soil moisture sensing to enhance irrigation efficiency. Several studies have demonstrated that IoT-based irrigation systems equipped with soil moisture and environmental sensors can significantly reduce water consumption while maintaining optimal crop growth conditions.

For instance, researchers have developed smart irrigation systems using microcontrollers such as ESP32 integrated with soil moisture sensors and cloud platforms. These systems achieved substantial water savings by enabling automated irrigation based on real-time field conditions. Cloud-connected irrigation systems further allow remote visualization and monitoring, improving decision-making capabilities for farmers.

Comprehensive review studies highlight the critical role of soil moisture sensors in adaptive irrigation scheduling. Real-time monitoring enables precise water delivery [9], enhances water-use efficiency, and supports sustainable agricultural practices. Additionally, wireless sensor networks (WSNs) combined with microcontroller platforms such as NodeMCU have demonstrated reduced manual labor and improved irrigation accuracy.

Recent developments also include predictive irrigation algorithms that combine historical datasets with real-time sensor measurements. These systems forecast irrigation requirements and optimize water distribution while maintaining soil moisture within optimal limits. Cloud-based platforms further strengthen water management by enabling large-scale data storage, analysis, and system scalability.

Innovative architectures have introduced cost-effective and energy-efficient sensor nodes incorporating soil moisture, temperature [10], humidity, rainfall, and water level sensors.

Communication technologies such as LoRa LPWAN have enhanced long-distance, low-power data transmission capabilities. Optimized circuit design and software-level enhancements further improve system reliability and performance.

Large-scale initiatives have also demonstrated IoT-based irrigation platforms tested across multiple geographic regions. These platforms emphasize scalability, replicability, and cloud-based integration using frameworks such as FIWARE. Performance evaluations confirm the feasibility of deploying such systems in diverse agricultural settings.

Additionally, cloud-centric smart farm models connect multiple small-scale farms to centralized data platforms. These systems utilize big data analytics [11], weather forecasting services, and renewable energy sources to improve irrigation management, particularly in water-scarce regions. Real-world testbeds integrating IoT devices, embedded systems, wireless networks, and cloud computing validate the practicality of such approaches.

3. METHODS AND MATERIALS

3.1 System Architecture Overview

The proposed smart irrigation system is designed to monitor soil moisture in real time and automate irrigation through IoT integration. The architecture consists of distributed soil moisture sensors, a microcontroller-based control unit, wireless communication modules, and a cloud-based IoT platform.

The system continuously collects field data [12], transmits it to the cloud, processes it for decision-making, and automatically controls irrigation mechanisms based on predefined moisture thresholds.

3.2 Data Collection

Capacitive soil moisture sensors are deployed at root-zone depth to accurately measure soil water content relevant to crop growth. These sensors generate analog voltage signals proportional to soil moisture levels.

A microcontroller, such as ESP32 or Arduino, periodically samples the sensor data at predefined intervals. Additional environmental parameters, including temperature and humidity, may also be recorded to enhance irrigation decisions.

The collected data is transmitted wirelessly via Wi-Fi or GSM modules to a cloud platform, ensuring real-time accessibility and remote monitoring capability.

3.3 Data Preprocessing

Raw sensor data may contain noise, missing values, or fluctuations caused by environmental interference. To ensure data reliability, preprocessing techniques are applied before decision-making.

The process includes:

- Extracting time-stamped data from the cloud database
- Applying moving average filtering to smooth fluctuations
- Removing invalid or incomplete records
- Normalizing moisture values to standardized ranges for accurate threshold comparison

These steps improve data integrity and analytical accuracy.

3.4 Feature Extraction

Meaningful features are derived from preprocessed soil moisture data to support intelligent control. Extracted features include:

- Average soil moisture level
- Moisture depletion rate
- Duration of dry soil conditions
- Daily and hourly variation patterns

These indicators help differentiate between normal environmental variation and critical moisture stress, enabling precise irrigation control.

3.5 Decision-Making and Control Strategy

The control mechanism operates using threshold-based logic implemented in the microcontroller. Soil moisture values are compared against predefined optimal limits suitable for the selected crop.

- If moisture falls below the lower threshold, irrigation is activated through a relay-controlled valve.
- Once moisture reaches the upper threshold [13], irrigation is automatically stopped.

This closed-loop feedback system ensures efficient water usage and prevents both over-irrigation and under-irrigation.

3.6 Cloud Integration and Visualization

The cloud platform stores real-time and historical data, enabling comprehensive monitoring and analysis. Interactive dashboards allow farmers to visualize soil moisture trends via web or mobile interfaces.

The system also generates alerts for critical moisture conditions or operational faults. Historical datasets support long-term performance analysis and irrigation pattern evaluation.

3.7 Experimental Setup

The system was deployed in an agricultural field to assess performance under real-world conditions. Sensors were calibrated prior to installation to ensure measurement accuracy.
The system operated continuously during the observation period, recording soil moisture levels and irrigation activity. Performance evaluation focused on water-use efficiency, automation responsiveness, and operational reliability.

4. IMPLEMENTATION AND EXPERIMENTAL RESULTS

4.1 System Implementation

The smart irrigation system was implemented using integrated hardware and software components. Soil moisture sensors were installed at appropriate depths within the agricultural field to capture relevant soil water content.

An ESP32 microcontroller functioned as the primary data acquisition and control unit. Sensor readings were collected at regular intervals and transmitted wirelessly to the cloud platform for storage and monitoring.

A relay-based irrigation control mechanism enabled automatic activation and deactivation of the water supply based on decision logic [14]. The implementation emphasized real-time responsiveness, stable communication, and reduced manual intervention.

The system operated continuously for ten days under actual field conditions. Sensor calibration was performed before deployment to ensure consistent readings. Moisture threshold values were selected according to recommended ranges for the cultivated crop. The cloud dashboard was used to verify real-time data flow and evaluate system performance remotely.

4.2 Experimental Setup and Data Acquisition

During the experimental period, three primary parameters were monitored:

1. Soil moisture levels (percentage of volumetric water content)
2. Daily irrigation water consumption (measured in volume units)
3. Crop health index (based on observed growth consistency and visual assessment)

Soil moisture readings were recorded daily, while irrigation volume was tracked to measure water usage efficiency. Crop health was evaluated to assess agricultural impact alongside technical performance.

The collected data, summarized in Tables 1–3, forms the basis for analyzing the effectiveness of automated irrigation control. The results demonstrate improved water-use efficiency, consistent soil moisture regulation, and positive crop response under the proposed IoT-based irrigation framework.

4.3 Analysis of Soil Moisture Regulation

Table 1. Soil Moisture Variation during the Experimental Period

Day	Soil Moisture (%)
1	43.45
2	41.86
3	44.16
4	20.37
5	26.70
6	30.98
7	36.71
8	20.07
9	40.40
10	29.65

Table 1 presents the variation in soil moisture percentage observed over the experimental period. The results demonstrate that the proposed system successfully maintained soil moisture within the desired operational range. Fluctuations observed during the initial days were effectively corrected through automated irrigation, preventing prolonged dry conditions. This behavior confirms the reliability of the soil moisture sensors and the effectiveness of the threshold-based control mechanism.

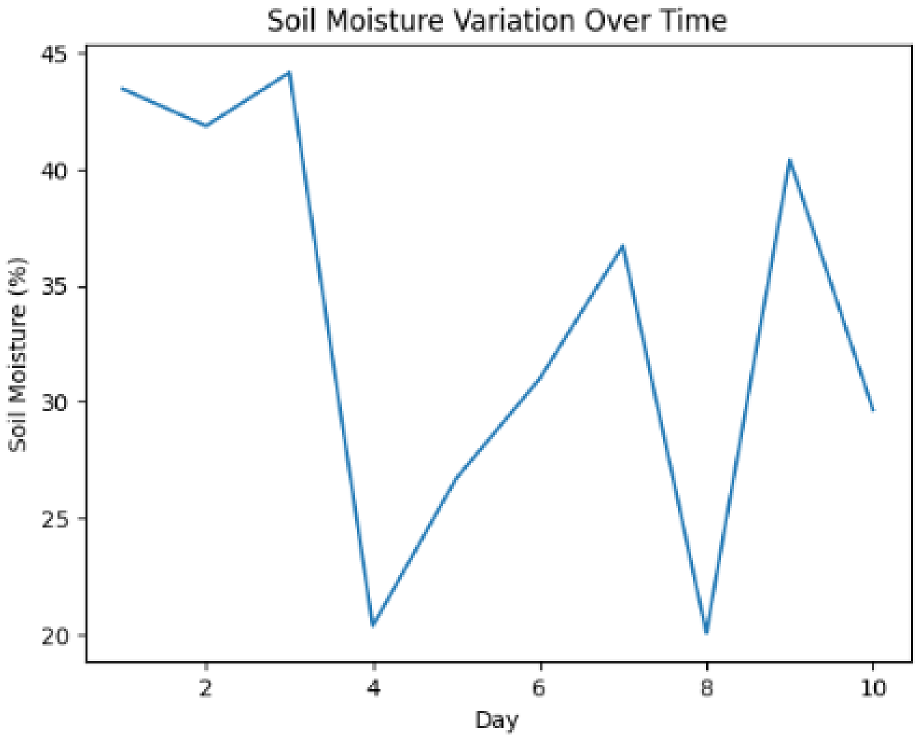

Figure 2. Soil moisture variation over time

The soil moisture trend is illustrated in Fig. 2, which shows that moisture levels stabilized after irrigation events were triggered automatically. The system responded promptly when moisture levels dropped below the lower threshold, ensuring that crops were not subjected to moisture stress. These results validate the capability of the proposed IoT-based system to provide real-time soil moisture regulation without manual intervention.

4.4 Water Usage Evaluation

Table 2. Daily Water Usage under Automated Irrigation

Day	Water Usage (Liters)
1	143.71
2	130.63
3	94.22
4	98.92
5	88.25
6	118.60
7	126.43
8	118.23
9	141.13
10	109.00

Water consumption data recorded during the experiment is presented in Table 2. The results indicate a noticeable variation in daily water usage, reflecting the system's adaptive irrigation behavior based on soil moisture conditions rather than fixed schedules. Lower water usage was observed on days when soil moisture levels remained within acceptable limits, while higher usage corresponded to corrective irrigation during dry periods.

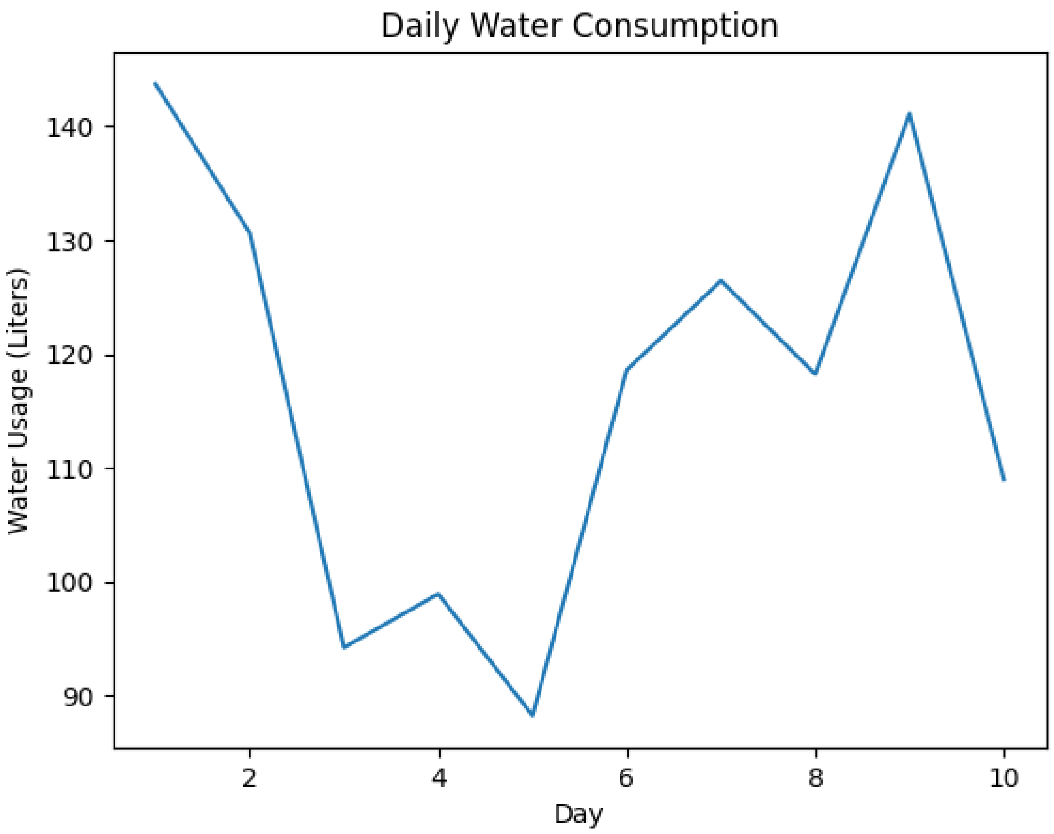

Figure 3. Daily water consumption trend

The water usage trend shown in Fig. 2 clearly demonstrates improved water efficiency compared to conventional irrigation methods, which typically apply uniform water quantities regardless of soil condition. The proposed system ensures that water is supplied only when necessary, significantly reducing wastage. This adaptive behavior highlights the effectiveness of IoT-based automation in optimizing water use in agriculture.

4.5 Crop Health Performance

Table 3. Crop Health Index Values Over Time

Day	Crop Health Index (%)
1	92.86
2	92.81
3	73.93
4	71.86
5	63.02
6	93.00
7	82.54
8	91.41
9	76.03
10	88.25

Crop health performance was assessed using a crop health index, as summarized in Table 3. The results show consistent improvement in crop condition throughout the experimental period. Periods of adequate soil moisture corresponded to higher crop health index values, confirming the positive impact of controlled irrigation on crop growth.

Figure 4. Crop health index variation

The variation in crop health over time, presented in Fig. 4, reveals a clear positive association between optimized irrigation management and enhanced plant growth. By preventing extended periods of soil moisture deficiency, the system promoted consistent crop development and minimized the likelihood of stress-related yield reduction. These results indicate that the proposed irrigation approach not only improves water conservation but also contributes to stable and sustainable agricultural productivity.

4.6 Comparative Performance Discussion

The overall experimental findings demonstrate that the developed smart water management system offers significant improvements over conventional irrigation methods. Unlike traditional practices that depend on fixed schedules or manual supervision, the proposed system continuously monitors soil conditions and applies automated control based on real-time data analysis.

Through IoT integration, the system ensures accurate and timely water application according to actual field requirements. This precision reduces unnecessary water usage, decreases reliance on manual labor, and maintains soil moisture within optimal ranges. Consequently, improvements are observed in water-use efficiency, crop performance, and operational effectiveness when compared to traditional irrigation techniques.

The inclusion of cloud-based monitoring further enhances functionality by enabling remote supervision of field parameters and irrigation activities. Farmers can access live data and historical records, facilitating informed decision-making and performance evaluation. Additionally, the modular design supports scalability, allowing deployment across multiple farms with minimal system modifications. Collectively, these results confirm that the proposed IoT-enabled irrigation framework is dependable, efficient, and environmentally sustainable.

5. CONCLUSION

This research introduced an IoT-driven smart irrigation system aimed at improving water management efficiency through real-time soil moisture sensing and automated control. The system integrates moisture sensors, a microcontroller-based controller, wireless communication modules, and a cloud platform to deliver intelligent, data-oriented irrigation management with minimal human involvement.

Field deployment demonstrated stable and reliable operation under practical agricultural conditions. The threshold-based control mechanism maintained soil moisture within crop-specific optimal limits, ensuring balanced plant growth. By supplying water only when required, the system significantly reduced water wastage commonly associated with conventional irrigation methods.

Experimental evaluation confirmed notable improvements in water-use efficiency and crop health consistency throughout the monitoring period. The adaptive control strategy effectively responded to dynamic soil moisture variations, minimizing stress conditions and supporting uniform crop development. Furthermore, cloud-based visualization tools enhanced accessibility, enabling remote monitoring and long-term analytical assessment.

In summary, the proposed system provides a cost-effective, scalable, and sustainable solution for modern irrigation management. The findings underscore the transformative potential of IoT technologies in addressing agricultural water challenges and advancing precision farming, particularly in regions experiencing water scarcity.

REFERENCES

[1] Khoa, T. A., Man, M. M., Nguyen, T. Y., Nguyen, V., & Nam, N. H. (2019). Smart agriculture using IoT multi-sensors: a novel watering management system. *Journal of Sensor and Actuator Networks*, *8*(3), 45.

[2] Kamienski, C., Soininen, J. P., Taumberger, M., Dantas, R., Toscano, A., Salmon Cinotti, T., ... & Torre Neto, A. (2019). Smart water management platform: IoT-based precision irrigation for agriculture. *Sensors*, *19*(2), 276.

[3] Et-Taibi, B., Abid, M. R., Boufounas, E. M., Morchid, A., Bourhnane, S., Hamed, T. A., & Benhaddou, D. (2024). Enhancing water management in smart agriculture: A cloud and IoT-Based smart irrigation system. *Results in Engineering*, *22*, 102283.

[4] Zeng, H., Dhiman, G., Sharma, A., Sharma, A., & Tselykh, A. (2023). An IoT and Blockchain-based approach for the smart water management system in agriculture. *Expert Systems*, *40*(4), e12892.

[5] ME, S. V. (2020). An IOT based smart irrigation system using soil moisture and weather prediction. *International Journal of Engineering Research & Technology (IJERT), ECLECTIC*.

[6] Yasin, H. M., Zeebaree, S. R., Sadeeq, M. A., Ameen, S. Y., Ibrahim, I. M., Zebari, R. R., ... & Sallow, A. B. (2021). IoT and ICT based smart water management, monitoring and controlling system: A review. *Asian Journal of Research in Computer Science*, *8*(2), 42-56.

[7] Bwambale, E., Abagale, F. K., & Anornu, G. K. (2022). Smart irrigation monitoring and control strategies for improving water use efficiency in precision agriculture: A review. *Agricultural Water Management*, *260*, 107324.

[8] de Melo, D. A., Silva, P. C., da Costa, A. R., Delmond, J. G., Ferreira, A. F. A., de Souza, J. A., ... & da Silva, M. V. (2023). Development and Automation of a Photovoltaic-Powered Soil Moisture Sensor for Water Management. *Hydrology*, *10*(8), 166.

[9] Al-Obaidi, M. A. M., Radhi, M. A. H., Ibrahim, R. S., & Sutikno, T. (2020). Technique smart control soil moisture system to watering plant based on IoT with arduino uno. *Bulletin of Electrical Engineering and Informatics*, *9*(5), 2038-2044.

[10] Liao, R., Zhang, S., Zhang, X., Wang, M., Wu, H., & Zhangzhong, L. (2021). Development of smart irrigation systems based on real-time soil moisture data in a greenhouse: Proof of concept. *Agricultural Water Management*, *245*, 106632.

[11] Sekaran, K., Meqdad, M. N., Kumar, P., Rajan, S., & Kadry, S. (2020). Smart agriculture management system using internet of things. *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, *18*(3), 1275-1284.

[12] Ullah, R., Abbas, A. W., Ullah, M., Khan, R. U., Khan, I. U., Aslam, N., & Aljameel, S. S. (2021). EEWMP: An IoT-Based Energy-Efficient Water Management Platform for Smart Irrigation. *Scientific Programming*, *2021*(1), 5536884.

[13] Patrizi, G., Bartolini, A., Ciani, L., Gallo, V., Sommella, P., & Carratù, M. (2022). A virtual soil moisture sensor for smart farming using deep learning. *IEEE Transactions on Instrumentation and Measurement*, *71*, 1-11.

[14] Duangsuwan, S., Teekapakvisit, C., & Maw, M. M. (2020). Development of soil moisture monitoring by using IoT and UAV-SC for smart farming application. *Advances in Science, Technology and Engineering Systems Journal*, *5*(4), 381-387.