PASCAL Journal of Computer Science and Informatics
https://jurnal.devitara.or.id/index.php/komputer
E-ISSN: 3047-5074 Volume 3 Nomor 2 Tahun 2026

Development and Performance Evaluation of an IoT-Based Smart Irrigation System for Real-Time Soil Moisture Monitoring and Automatic Irrigation

[1]Siti Rubiah, Tasya Halizha Lubis, Haryoko Ichsan Prabowo, Dina Lorensa Sinaga, [5]Sony Bahagia Sinaga
[1, 2, 3, 4] Informatics Study Program, Universitas Budi Darma, Medan, North Sumatra, Indonesia
[5]STMIK Mulia Darma, Rantauprapat, Indonesia

ARTICLE INFO

Keywords:
Internet of Things,
Smart Irrigation System,
ESP32,
Soil Moisture,
Real-Time Monitoring.

Email :
rubyhsb95@gmail.com

ABSTRACT

Manual irrigation management often results in watering practices that do not reflect actual soil moisture conditions, leading to inefficient water use and reduced crop productivity. This study aims to design and implement an Internet of Things (IoT)-based Smart Irrigation System capable of monitoring soil moisture in real time while automatically controlling the irrigation process. The research employed a Research and Development (R&D) method using a prototyping approach, including requirement identification, system design, hardware and software implementation, system integration, and performance testing. The proposed system was developed using an ESP32 microcontroller, a capacitive soil moisture sensor, a relay module, a water pump, and an internet-based monitoring dashboard. System performance was evaluated through sensor readings, real-time data monitoring, automatic pump control, response time measurement, and operational stability testing. The results demonstrate that the proposed system successfully monitors soil moisture, transmits data to the dashboard in real time, and automatically controls the irrigation pump based on predefined soil moisture thresholds. The implementation of a threshold with hysteresis mechanism improves pump stability by reducing frequent switching caused by sensor fluctuations. Furthermore, the system exhibits a relatively fast response time and stable operation throughout the testing period. These findings indicate that IoT technology provides an effective solution for developing efficient, practical, and scalable smart irrigation systems suitable for small- and medium-scale agricultural applications.

INTRODUCTION

Agriculture plays a strategic role in ensuring food security while supporting economic growth. However, agricultural productivity continues to face significant challenges, one of which is inefficient irrigation management. Increasing water scarcity due to climate change, rising water demand across multiple sectors, and inappropriate irrigation practices have significantly affected water-use efficiency and crop productivity. Irrigation systems that do not consider actual soil moisture conditions may lead to excessive water consumption or insufficient irrigation, both of which negatively affect plant growth. Therefore, developing irrigation systems capable of supplying water according to the actual moisture requirements of the soil has become increasingly important for sustainable agricultural practices.

Soil moisture is one of the most critical parameters influencing plant growth and water availability. Soil moisture levels below the optimum threshold may cause plants to experience water stress, whereas excessive moisture reduces soil aeration, inhibits root development, and increases the risk of plant diseases. Fu et al. (2024) reported that proper soil moisture management plays a vital role in maintaining crop productivity while improving irrigation efficiency. Nevertheless, irrigation practices in small- and medium-scale farming are still predominantly performed manually based on farmers' experience or visual observation of soil conditions. Such conventional approaches are subjective and often result in inaccurate irrigation decisions, leading to inefficient water use and increased operational costs.

Recent advances in the Internet of Things (IoT) have provided new opportunities to address these challenges through the integration of sensors, microcontrollers, actuators, and wireless communication technologies into intelligent irrigation systems. In IoT-based irrigation, soil moisture sensors continuously monitor the moisture content of the growing medium, while a microcontroller processes the collected data to determine irrigation requirements. The processed information is then transmitted to an online monitoring platform, allowing users to observe field conditions remotely in real time and enabling automatic irrigation control based on predefined moisture thresholds (Obaideen et al., 2022).

Numerous studies have investigated IoT-based smart irrigation systems using different approaches. Aisyah et al. (2025) developed an automatic irrigation system utilizing an ESP32 microcontroller and a soil moisture sensor to activate irrigation based on predefined moisture thresholds. Rohman (2025) integrated soil moisture, temperature, and rainfall sensors into an IoT monitoring platform, enabling real-time environmental monitoring. Similarly, Ardianto et al. (2025) incorporated soil moisture sensors, DHT22 sensors, and renewable energy sources to improve the energy efficiency of automatic irrigation systems. Meanwhile, Agustirandi et al. (2024) emphasized the importance of sensor calibration in improving the accuracy and reliability of soil moisture measurements in IoT-based agricultural applications.

Although previous studies have demonstrated the feasibility of implementing IoT technology in irrigation systems, several limitations remain. Most existing studies primarily focus on hardware implementation or the functionality of automatic irrigation without comprehensively evaluating system performance. Critical aspects such as actuator response time, data transmission intervals, operational stability, and sensor calibration procedures have received limited attention. These performance indicators are essential for assessing the reliability and practical applicability of smart irrigation systems before deployment in real agricultural environments. Furthermore, several studies emphasize either environmental monitoring or automatic irrigation independently, while comprehensive integration and evaluation of both functionalities remain limited.

To address these research gaps, this study develops an Internet of Things (IoT)-based Smart Irrigation System using a capacitive soil moisture sensor, an ESP32 microcontroller, a relay module, a water pump, and an internet-based monitoring dashboard. The proposed system performs real-time soil moisture monitoring while automatically controlling irrigation based on predefined soil moisture thresholds. Unlike previous studies, this research not only presents the implementation of the smart irrigation system but also evaluates its performance through sensor calibration, response time analysis, data transmission performance, and operational stability testing. These evaluations provide a more comprehensive assessment of the system's reliability for practical irrigation applications.

This study aims to design, implement, and evaluate the performance of an IoT-based Smart Irrigation System as an automatic irrigation solution for small- and medium-scale agricultural applications. The findings are expected to contribute to the development of more efficient, practical, and reliable smart agriculture technologies. Furthermore, the proposed system provides a foundation for future research involving additional environmental sensors, predictive irrigation models, and artificial intelligence-based decision-making algorithms to further enhance irrigation efficiency and agricultural sustainability.

METHODS

Research Design

This study employed a Research and Development (R&D) methodology using a prototyping approach to design, develop, and evaluate an Internet of Things (IoT)-based Smart Irrigation System. The prototyping approach was selected because it enables iterative system development, allowing hardware and software components to be integrated, tested, and refined based on system performance.

The research consisted of seven sequential stages: (1) problem identification, (2) literature review, (3) system design, (4) hardware implementation, (5) software development, (6) system integration, and (7) system testing and performance evaluation.

System Architecture

The proposed Smart Irrigation System consists of four major components: data acquisition, processing, communication, and actuation. Soil moisture data are collected using a capacitive soil moisture sensor installed in the planting medium. The sensor continuously measures the moisture level and transmits the readings to an ESP32 microcontroller, which functions as the central processing unit of the system.

The ESP32 processes the acquired sensor data and compares the measured soil moisture with predefined threshold values. Based on this decision-making process, the controller automatically activates or deactivates

PASCAL Journal of Computer Science and Informatics
https://jurnal.devitara.or.id/index.php/komputer
E-ISSN: 3047-5074 Volume 3 Nomor 2 Tahun 2026

a relay module connected to a DC water pump. Simultaneously, the ESP32 transmits soil moisture data via a Wi-Fi network to an IoT dashboard, enabling users to monitor soil conditions remotely in real time. The overall architecture of the proposed system is presented in Figure 2.

Figure 1. Architecture of the IoT-Based Smart Irrigation System

Hardware and Software Components

The developed system integrates both hardware and software components to support data acquisition, processing, wireless communication, automatic irrigation control, and real-time monitoring.

Table 1. Hardware and Software Components

No.	Component	Function
1	ESP32 Microcontroller	Central controller and Wi-Fi communication
2	Capacitive Soil Moisture Sensor	Measures soil moisture level
3	Single-Channel Relay Module	Controls water pump operation
4	DC Water Pump	Performs automatic irrigation
5	12 V Power Adapter	Provides electrical power
6	Arduino IDE	Develops and uploads ESP32 firmware
7	IoT Dashboard	Displays real-time monitoring data

System Algorithm

The Smart Irrigation System operates autonomously by periodically acquiring soil moisture data from the capacitive sensor. The analog sensor readings are converted into soil moisture percentages using calibration parameters obtained during the calibration process.

The calculated soil moisture value is compared with two predefined threshold values. When the measured soil moisture falls below 40%, the ESP32 activates the relay module, turning on the water pump to irrigate the soil. Conversely, when soil moisture reaches 60%, the relay is deactivated, stopping the irrigation process.

To prevent rapid switching caused by sensor fluctuations around the threshold values, the proposed system applies a threshold-based hysteresis control strategy. Additionally, soil moisture data are periodically transmitted to the IoT dashboard, enabling continuous real-time monitoring. The system algorithm is illustrated in Figure 2.

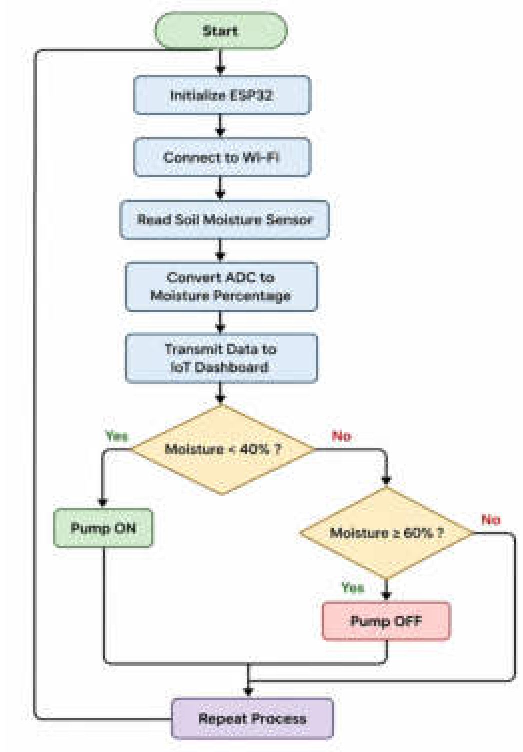

Figure 2. Flowchart of the Proposed System

Sensor Calibration

Prior to system testing, the capacitive soil moisture sensor was calibrated to establish reference values under dry and saturated soil conditions. The calibration process was performed by recording the Analog-to-Digital Converter (ADC) values obtained from both conditions. The soil moisture percentage was calculated using Equation (1).

$$SM = \frac{ADC_{dry} - ADC_{reading}}{ADC_{dry} - ADC_{wet}} \times 100\%$$

where:

SM = Soil moisture (%)
ADCreading = Sensor reading
ADCdry = ADC value under dry soil conditions
ADCwet = ADC value under saturated soil conditions

Based on the calibration results, two control thresholds were established. The irrigation system automatically activates the water pump when soil moisture falls below 40% and stops irrigation when soil moisture reaches 60%. This hysteresis-based control mechanism minimizes frequent relay switching caused by small fluctuations in sensor measurements.

System Performance Evaluation

Performance evaluation was conducted after all hardware and software components had been successfully integrated. The objective was to evaluate the effectiveness and reliability of the proposed Smart Irrigation System under normal operating conditions.

Five performance indicators were evaluated: sensor accuracy, real-time monitoring capability, automatic irrigation control, system response time, and operational stability.

Table 2. Performance Evaluation Parameters

No.	Parameter	Evaluation Method	Success Indicator
1	Soil moisture sensing	Measure soil moisture under dry, moist, and wet conditions	Sensor readings vary according to soil conditions
2	Real-time monitoring	Transmit data through Wi-Fi to the IoT dashboard	Data displayed successfully in real time
3	Automatic irrigation	Evaluate relay operation based on moisture thresholds	Pump activates and deactivates automatically
4	Response time	Measure the interval between sensor detection and pump activation	Response time < 3 seconds
5	System stability	Continuous operation for 72 hours	No system malfunction or communication failure

Data Analysis

Experimental data were analyzed using descriptive quantitative analysis. The collected data included soil moisture measurements, system response time, data transmission performance, and automatic irrigation results. The experimental results were presented in tables and graphical visualizations to evaluate the performance of the proposed system. Furthermore, the observed performance indicators were compared with the predefined research objectives to determine the effectiveness of the IoT-based Smart Irrigation System in providing reliable real-time monitoring and automatic irrigation control.

RESULTS AND DISCUSSION

Results

System Implementation

The implementation phase was carried out after the completion of the hardware and software design processes. The developed Smart Irrigation System integrates an ESP32 microcontroller as the central processing unit, a capacitive soil moisture sensor for environmental data acquisition, a single-channel relay module as the switching actuator, a DC water pump for irrigation, and an IoT-based dashboard for real-time monitoring.

During system operation, the capacitive sensor continuously measures the soil moisture level at predefined intervals. The acquired data are processed by the ESP32 to determine the current soil condition based on predetermined moisture thresholds. The processed data are subsequently transmitted via a Wi-Fi network to the IoT dashboard, enabling users to monitor soil moisture remotely in real time. When the measured soil moisture falls below the minimum threshold, the ESP32 automatically activates the relay module to start the irrigation pump. Conversely, the pump is deactivated automatically once the soil moisture reaches the predefined upper threshold.

The successful integration of all hardware and software components demonstrates that the proposed system is capable of performing both real-time soil moisture monitoring and automatic irrigation control within a single IoT platform.

Soil Moisture Sensor Calibration

Sensor calibration was conducted to establish reference ADC values under dry and saturated soil conditions. These reference values were subsequently used to convert raw sensor readings into soil moisture percentages.

Several calibration experiments were performed using different soil moisture conditions. The average calibration results are presented in Table 3.

Table 3. Soil Moisture Sensor Calibration Results

Soil Condition	ADC Value
Dry	3050
Moist	2250
Wet	1450

The calibration results indicate that the ADC value decreases as soil moisture increases. This inverse relationship confirms that the capacitive soil moisture sensor can effectively distinguish different soil moisture conditions. The calibration parameters were then employed to convert ADC values into soil moisture percentages for subsequent monitoring and automatic irrigation control.

Real-Time Soil Moisture Monitoring

Following sensor calibration, the developed system was evaluated under real operating conditions to verify its real-time monitoring capability. The experiment monitored changes in soil moisture during the irrigation process. The monitoring results are summarized in Table 4.

Table 4. Real-Time Soil Moisture Monitoring Results

Time	Soil Moisture (%)	Pump Status
08:00	32	ON
08:05	38	ON
08:10	45	OFF
08:15	53	OFF
08:20	60	OFF

As shown in Table 4, soil moisture gradually increased after irrigation commenced. The collected data were successfully transmitted to the IoT dashboard with negligible communication delay, allowing users to observe soil conditions continuously in real time.

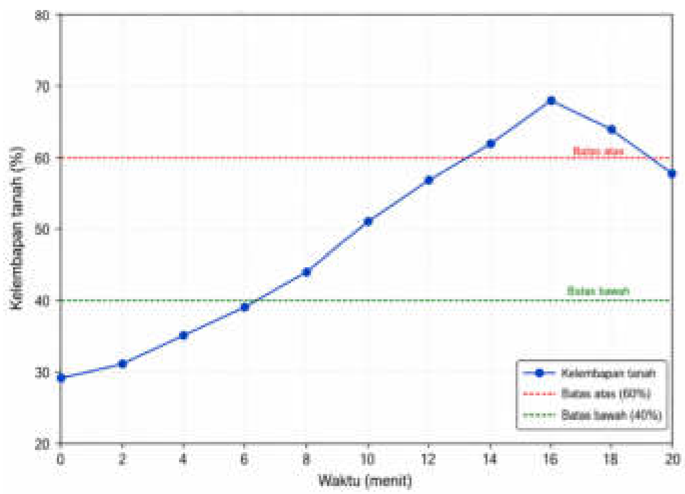

Figure 3. IoT Monitoring

Automatic Irrigation Performance

The automatic irrigation function was evaluated to verify the system's capability to control the irrigation pump according to predefined soil moisture thresholds. The experimental results are presented in Table 5.

Table 5. Automatic Irrigation Performance

Soil Moisture	Relay Status	Pump
30%	ON	Running
35%	ON	Running
45%	OFF	Stopped
55%	OFF	Stopped
65%	OFF	Stopped

The experimental results demonstrate that the proposed threshold-based hysteresis control algorithm successfully regulates irrigation automatically. The irrigation pump is activated only when soil moisture falls below 40% and remains active until the moisture reaches 60%. This hysteresis strategy effectively minimizes unnecessary relay switching caused by minor fluctuations around the control threshold, thereby improving actuator stability and potentially extending the operational lifespan of the irrigation pump.

System Response Time

System response time was measured as the interval between soil moisture detection below the minimum threshold and the activation of the irrigation pump. Ten independent experiments were conducted under identical testing conditions.

Table 6. System Response Time

Test	Response Time (s)
1	2.3
2	2.4
3	2.5
4	2.4
5	2.3
6	2.5
7	2.4
8	2.4
9	2.3
10	2.4

The average response time of the developed system was 2.39 seconds, indicating rapid system performance following the detection of dry soil conditions. This response time is primarily influenced by sensor acquisition time, ESP32 data processing, wireless communication, and relay activation.

System Stability Evaluation

Long-term stability testing was conducted by operating the Smart Irrigation System continuously for 72 hours. The evaluation results are summarized in Table 7.

Table 7. System Stability Test Results

Parameter	Result
Testing Duration	72 hours
Sensor Failure	None
Relay Failure	None
Data Transmission Failure	0
System Restart	0

Throughout the testing period, the developed system operated continuously without hardware malfunction, communication interruption, or software instability. Soil moisture data were transmitted periodically to the monitoring dashboard, while automatic irrigation control functioned consistently according to the predefined moisture thresholds.

Discussion

The experimental results demonstrate that the proposed Smart Irrigation System successfully integrates real-time soil moisture monitoring and automatic irrigation control within a single Internet of Things (IoT) platform. This integration enables continuous observation of soil conditions while reducing dependence on manual irrigation practices, thereby improving irrigation efficiency and reducing water consumption.

The calibration process established reliable ADC reference values corresponding to different soil moisture conditions, allowing accurate conversion of sensor readings into soil moisture percentages. These findings are consistent with those reported by Agustirandi et al. (2024), who emphasized that sensor calibration is a critical step in improving the accuracy and reliability of capacitive soil moisture measurements in IoT-based agricultural systems.

The implementation of a threshold-based hysteresis control strategy proved effective in maintaining stable irrigation performance. By employing separate activation (40%) and deactivation (60%) thresholds, the proposed system prevents excessive relay switching caused by sensor fluctuations near the decision boundary. Similar control strategies have been widely adopted in smart irrigation systems because they improve actuator reliability and reduce unnecessary mechanical wear.

From a performance perspective, the average system response time of 2.39 seconds indicates that the proposed system responds rapidly to changes in soil moisture conditions. The response time includes sensor acquisition, data processing by the ESP32 microcontroller, relay activation, and wireless communication. Furthermore, the successful 72-hour continuous operation without sensor failure, communication loss, or system restart demonstrates the robustness and operational stability of the developed prototype.

Overall, the experimental findings confirm that the proposed IoT-based Smart Irrigation System fulfills the objectives of this study by providing an efficient, reliable, and cost-effective solution for real-time soil moisture monitoring and automatic irrigation. The developed prototype is particularly suitable for small- and medium-scale agricultural applications and provides a practical foundation for future research involving additional environmental sensors, predictive irrigation models, and artificial intelligence-based decision support systems.

CONCLUSION

This study successfully designed, developed, and implemented an Internet of Things (IoT)-based Smart Irrigation System utilizing an ESP32 microcontroller, a capacitive soil moisture sensor, a relay module, a DC water pump, and an IoT monitoring dashboard to enable real-time soil moisture monitoring and automatic irrigation control. The experimental results demonstrated that the proposed system effectively detected variations in soil moisture, periodically transmitted sensor data to the monitoring dashboard, and automatically controlled irrigation based on predefined moisture thresholds using a threshold-based hysteresis control strategy. This approach ensured stable pump operation by activating irrigation when soil moisture fell below the lower threshold and deactivating it once the upper threshold was reached, thereby minimizing unnecessary relay switching caused by sensor fluctuations. Furthermore, the system exhibited a relatively fast response time and maintained stable performance throughout the testing period, indicating its reliability for practical agricultural applications. The primary contribution of this research lies in the development of a simple, cost-effective, and integrated IoT platform that combines real-time monitoring, automatic irrigation, and system performance evaluation into a single solution suitable for small- and medium-scale agricultural environments. The proposed system provides a practical foundation for the adoption of smart agriculture technologies and may contribute to improving irrigation efficiency and water resource management. Future research should focus on integrating additional environmental sensors, such as air temperature, relative humidity, light intensity, and rainfall sensors, to support more adaptive irrigation decision-making. Moreover, incorporating Artificial Intelligence (AI) or Machine Learning (ML) techniques to predict crop water requirements based on historical and environmental data could further enhance irrigation efficiency, decision accuracy, and overall system reliability.

REFERENCES

Abioye, E. A., Abidin, M. S. Z., Mahmud, M. S. A., Buyamin, S., Ishak, M. H. I., Rahman, M. K. I. A., Otuoze, A. O., Ramli, M. S. A., & Ijike, O. D. (2021). A review on monitoring and advanced control strategies for precision irrigation. Computers and Electronics in Agriculture, 173, 105441. https://doi.org/10.1016/j.compag.2020.105441

Agustirandi, B., Inayah, I., Aminah, N. S., & Budiman, M. (2024). Analysis, comparison, calibration, and application of low-cost soil moisture sensors in smart agriculture based on the Internet of Things. TELKOMNIKA (Telecommunication Computing Electronics and Control), 22(5). https://doi.org/10.12928/TELKOMNIKA.v22i5.25703

Aisyah, N., Ulhaq, E. D., Dharmawan, A., & Purbakawaca, R. (2025). Design of an IoT-based smart irrigation system using soil moisture sensors. Journal of Engineering Research, 11(1), 89–97.

Ardianto, A. F., Rahmasari, E. S., & Pratama, A. P. (2025). Smart irrigation system berbasis IoT dengan sensor soil moisture dan DHT22 menggunakan sumber daya terbarukan. Jurnal Teknologi Informasi dan Komunikasi, 500–511.

Fu, Z., Zhang, Y., Liu, X., et al. (2024). Global critical soil moisture thresholds of plant water stress. Nature Communications, 15, Article 49244. https://doi.org/10.1038/s41467-024-49244-7

Jawad, H. M., Nordin, R., Gharghan, S. K., Jawad, A. M., & Ismail, M. (2017). Energy-efficient wireless sensor networks for precision agriculture: A review. Sensors, 17(8), 1781. https://doi.org/10.3390/s17081781

Kamienski, C., Soininen, J. P., Taumberger, M., et al. (2019). Smart water management platform: IoT-based precision irrigation for agriculture. Sensors, 19(2), 276. https://doi.org/10.3390/s19020276

Liakos, K. G., Busato, P., Moshou, D., Pearson, S., & Bochtis, D. (2018). Machine learning in agriculture: A review. Sensors, 18(8), 2674. https://doi.org/10.3390/s18082674

Obaideen, K., AlMallahi, M. N., Alami, A. H., Ramadan, M., Abdelkareem, M. A., & Olabi, A. G. (2022). An overview of smart irrigation systems using IoT. Energy Nexus, 7, 100124. https://doi.org/10.1016/j.nexus.2022.100124

Ojha, T., Misra, S., & Raghuwanshi, N. S. (2015). Wireless sensor networks for agriculture: The state-of-the-art in practice and future challenges. Computers and Electronics in Agriculture, 118, 66–84. https://doi.org/10.1016/j.compag.2015.08.011

Rohman, F. N. (2025). Sistem smart irrigation berbasis IoT dengan monitoring kelembapan tanah, suhu, dan deteksi hujan. Jurnal Teknologi Informasi dan Komputer, 2(3), 695–710.