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# Design and Implementation of IoT-Based Soil Moisture Monitoring and Automatic Irrigation System Using ESP32

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ABSTRACT

Proper soil moisture management plays an essential role in supporting plant growth and improving water-use efficiency. Manual irrigation is still widely practiced and often ignores the actual soil moisture condition, leading to either excessive or insufficient watering. This study aims to design and implement an Internet of Things (IoT)-based soil moisture monitoring and automatic water pump control system using the ESP32 microcontroller. The research employed a Research and Development (R&D) approach through prototype development, including literature review, system requirement analysis, hardware and software design, system implementation, sensor calibration, and performance evaluation. The proposed system integrates a capacitive soil moisture sensor, relay module, 12 V DC water pump, and the Blynk platform for real-time monitoring. A hysteresis control strategy was implemented by setting the lower and upper soil moisture thresholds at 40% and 60%, respectively, to improve pump stability. Experimental results demonstrated that the developed system achieved an average sensor error of 3.42%, an average response time of 2.14 seconds, and maintained soil moisture within the range of 50.9%–54.2% during a seven-day evaluation period. Furthermore, the system reduced water consumption by 31.6% compared with conventional manual irrigation. These findings indicate that the proposed IoT-based system is capable of providing reliable real-time soil moisture monitoring and efficient automatic irrigation, making it suitable for potted plants, home gardens, and small-scale greenhouse applications.



## INTRODUCTION

Water is one of the most essential factors influencing plant growth and productivity because it plays a vital role in physiological processes, including photosynthesis, nutrient transportation, and tissue development. Inadequate water supply may adversely affect plant growth, resulting in water stress, reduced productivity, and even crop failure. Conversely, excessive irrigation may decrease soil oxygen availability, promote root rot, and increase the risk of plant diseases (Sirait & Aprilia, 2020). Therefore, irrigation management should be performed based on actual soil moisture conditions to maintain optimal soil water content according to plant requirements.

In small-scale agriculture and household gardening, irrigation is still predominantly performed manually according to users' estimations or predetermined schedules. Although this approach is simple and inexpensive, it often leads to inefficient water utilization because it does not consider the real-time moisture condition of the soil. Environmental factors such as temperature, solar radiation, air humidity, and soil characteristics continuously influence soil moisture dynamics, making fixed irrigation schedules less effective (Gong et al., 2022).

The rapid development of the Internet of Things (IoT) has created new opportunities for improving irrigation management through real-time environmental monitoring. IoT technology enables sensors, microcontrollers, actuators, and communication devices to exchange data via the Internet, allowing users to monitor environmental conditions remotely using smartphones or computers. By integrating soil moisture sensors with automatic irrigation systems, water can be supplied only when required, thereby improving irrigation efficiency while reducing unnecessary water consumption (Aisyah et al., 2025).

Among various IoT platforms, the ESP32 microcontroller has become one of the most widely adopted devices because it integrates Wi-Fi and Bluetooth communication within a single low-cost module. This capability allows ESP32 to perform sensor data acquisition, data processing, actuator control, and cloud communication without requiring additional communication hardware. Furthermore, its low power consumption and sufficient input/output pins make ESP32 highly suitable for smart agriculture and environmental monitoring applications (Afifah, 2026).

Soil moisture sensors represent the primary sensing component in automatic irrigation systems. Two types of sensors are commonly employed, namely resistive and capacitive soil moisture sensors. Resistive sensors directly measure electrical resistance through metal probes inserted into the soil, making them susceptible to corrosion after prolonged use. In contrast, capacitive soil moisture sensors estimate water content based on changes in capacitance, providing better durability and long-term stability. Nevertheless, capacitive sensors still require calibration to convert analog readings into reliable soil moisture percentages suitable for irrigation control (Aisyah et al., 2025).

Several previous studies have investigated IoT-based automatic irrigation systems using ESP32 and soil moisture sensors. Aisyah et al. (2025) developed a smart irrigation system capable of reducing water consumption through automatic soil moisture-based irrigation. Ardianto et al. (2025) integrated soil moisture and DHT22 sensors with renewable energy sources to simultaneously monitor multiple environmental parameters. Wijaya et al. (2023) implemented an automatic watering system for microgreen cultivation and demonstrated that automation improved irrigation efficiency. Likewise, Purnama et al. (2024) developed an ESP32-based irrigation control system that supports sustainable agricultural practices through automatic irrigation management.

Although previous studies have demonstrated the effectiveness of IoT technologies in improving irrigation efficiency, most of them primarily focused on system implementation and communication performance. Comprehensive evaluations involving sensor accuracy, response time, hysteresis-based control stability, and water-use efficiency have received relatively limited attention. Furthermore, only a few studies have quantitatively compared automatic irrigation with conventional manual watering to evaluate water-saving performance.

Based on these research gaps, this study develops an IoT-based soil moisture monitoring and automatic irrigation system using an ESP32 microcontroller, a capacitive soil moisture sensor, a relay module, a DC water pump, and the Blynk platform for real-time monitoring. Unlike previous studies, this research not only implements an automatic irrigation system but also comprehensively evaluates its performance through sensor calibration, accuracy testing, response time measurement, communication stability assessment, and comparative analysis of water consumption between automatic and manual irrigation methods. The proposed system is expected to provide a low-cost and efficient irrigation solution suitable for potted plants, home gardens, and small-scale greenhouse applications.

The objective of this study is to design and implement an Internet of Things (IoT)-based soil moisture monitoring and automatic irrigation system using the ESP32 microcontroller. Additionally, this study evaluates the accuracy of the capacitive soil moisture sensor, measures the system response time, assesses the reliability of automatic pump control, and analyzes water-use efficiency compared with conventional manual irrigation.

## METHODS

### Research Design

This study employed a Research and Development (R&D) approach using a prototype development method to design and implement an Internet of Things (IoT)-based soil moisture monitoring and automatic irrigation system. The prototype development approach was selected because the primary objective of this study was to develop and evaluate a functional system capable of monitoring soil moisture in real time while automatically controlling water irrigation based on soil moisture conditions.

The research was conducted through several sequential stages, including literature review, system requirement analysis, hardware design, software development, system implementation, sensor calibration, system testing, data analysis, and conclusion drawing. These stages were systematically performed to ensure that the developed system satisfied both functional and non-functional requirements.

### Research Procedure

The research procedure is illustrated in Figure 1.

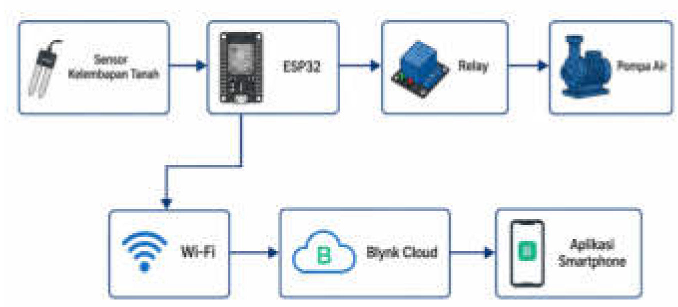


Figure 1. Block Diagram of the IoT-Based Soil Moisture Monitoring and Automatic Irrigation System

**Literature Review**

The first stage involved reviewing scientific literature related to Internet of Things (IoT), ESP32 microcontrollers, capacitive soil moisture sensors, relay modules, DC water pumps, the Blynk platform, and previous studies on smart irrigation systems. This stage aimed to establish the theoretical foundation, identify research gaps, and determine the appropriate hardware and software components for system development.

**System Requirement Analysis**

The second stage focused on identifying both functional and non-functional system requirements. The functional requirements included soil moisture sensing, real-time data transmission, automatic pump control, pump status monitoring, and manual control through the Blynk application. The non-functional requirements emphasized system reliability, ease of operation, low implementation cost, rapid response, and stable communication performance.

**Hardware Design**

The hardware architecture consisted of an ESP32 DevKit V1 microcontroller, a capacitive soil moisture sensor, a single-channel relay module, a 12-V DC water pump, a power adapter, an LM2596 step-down converter, water tubing, a water reservoir, and humus soil as the planting medium. The soil moisture sensor was connected to the analog input pin of the ESP32, while the relay module was connected to a digital output pin to control the water pump.

**Software Development**

The embedded software was developed using the Arduino IDE with C++ programming language. The software was designed to acquire analog sensor readings, convert them into soil moisture percentages, transmit monitoring data to the Blynk cloud platform via Wi-Fi, and automatically control the water pump based on predefined soil moisture thresholds.

The irrigation control algorithm implemented a hysteresis control mechanism by setting the lower and upper moisture thresholds at 40% and 60%, respectively. The pump was activated when soil moisture fell below 40% and deactivated once the moisture level reached or exceeded 60%. This hysteresis mechanism prevents excessive relay switching caused by small fluctuations around the threshold values.

**System Implementation**

All hardware components were assembled according to the proposed design. The capacitive soil moisture sensor was inserted approximately 5 cm into the planting medium. The ESP32 was connected to a Wi-Fi network and synchronized with the Blynk application to enable real-time monitoring through a smartphone.

**Sensor Calibration**

Sensor calibration was performed under two extreme soil conditions, namely completely dry soil and fully saturated soil. The analog values obtained from these conditions were used as the minimum and maximum calibration references for converting analog readings into soil moisture percentages.

The soil moisture percentage was calculated using Equation (1):

$$Soil\ Moisture\ (\%) = \frac{Dry\ Value - Sensor\ Value}{\text{Dry Value} - \text{Sensor Value}}\ X\ 100$$

To evaluate sensor accuracy, the converted moisture values were compared with measurements obtained from a commercial soil moisture meter.

The percentage error was calculated using Equation (2):

$$Eror\ (\%) = \frac{Reference\ Value - Sensor\ Value}{Reference\ Value}\ X\ 100$$

**System Testing**

The developed prototype was evaluated over a period of seven consecutive days using humus soil as the planting medium. Soil moisture measurements were recorded every two hours from 08:00 to 20:00. The evaluation focused on the following performance parameters:

a. Soil moisture percentage;
b. Water pump operating status;
c. System response time;
d. Water consumption;
e. IoT communication performance;
f. Wi-Fi connection stability.

Furthermore, the proposed automatic irrigation system was compared with conventional manual irrigation using a fixed daily water volume of 900 mL to evaluate water-use efficiency.

**Research Variables**

The independent variable in this study was the soil moisture level measured by the capacitive soil moisture sensor. The dependent variables included:

a. Water pump operating status;
b. System response time;
c. Water consumption;
d. Sensor measurement accuracy;
e. IoT monitoring performance.

The controlled variables consisted of the planting medium (humus soil), sensor type, water pump specification, power supply, sensor sampling interval, and soil moisture control thresholds of 40%–60%.

**Data Collection**

Experimental data were collected through direct observation of the developed prototype during system operation. Sensor readings were periodically recorded and compared with measurements obtained from the reference soil moisture meter. The collected data included:

a. Analog sensor values;
b. Converted soil moisture percentages;
c. Pump response time;
d. Relay operating status;
e. Number of pump activations;
f. Daily water consumption during the testing period.

**Data Analysis**

The collected data were analyzed using a quantitative descriptive approach. Several performance indicators were calculated to evaluate the effectiveness of the proposed system, including:

a. Average soil moisture;
b. Average sensor error;
c. Average system response time;
d. Number of pump activations;

e. Water consumption;
f. Water-use efficiency.
Water-use efficiency was calculated using Equation (3)

$$\text{Water Saving (\%)} = \frac{\text{Manual Water} - \text{Automatic Water}}{\text{Manual Water}} X\ 100$$

The analysis results were used to evaluate the system's capability to maintain soil moisture within the desired range, automatically control irrigation, improve irrigation efficiency, and provide reliable real-time monitoring through the IoT platform.

## RESULTS AND DISCUSSION

### System Implementation

The proposed IoT-based soil moisture monitoring and automatic irrigation system was successfully implemented using an ESP32 microcontroller, a capacitive soil moisture sensor, a single-channel relay module, a 12 V DC water pump, and the Blynk platform for real-time monitoring. The soil moisture sensor continuously measured the moisture content of the planting medium, while the ESP32 processed the acquired data and determined the operating status of the water pump according to the predefined irrigation algorithm.

Experimental observations demonstrated that all hardware components operated according to the proposed design. The ESP32 successfully acquired sensor readings, transmitted monitoring data to the Blynk application through a Wi-Fi network, and controlled the relay module based on the measured soil moisture level. When the soil moisture dropped below 40%, the water pump was automatically activated, whereas irrigation stopped when the moisture level reached 60% or higher. This control strategy effectively implemented a hysteresis mechanism, preventing frequent relay switching caused by minor fluctuations around the threshold values.

### Soil Moisture Sensor Calibration

Sensor calibration was performed to establish the relationship between analog sensor readings and soil moisture percentage. The analog value obtained under completely dry soil conditions was 3070, whereas saturated soil produced an analog value of 1280. These values were subsequently used as calibration references for converting analog readings into soil moisture percentages.

Table 1. Soil Moisture Sensor Calibration Results

| Soil Condition | Average Analog Value | Converted Soil Moisture |
|---|---|---|
| Completely dry soil | 3070 | 0% |
| Slightly dry soil | 2470 | 33.5% |
| Moist soil | 1980 | 60.9% |
| Wet soil | 1580 | 83.2% |
| Fully saturated soil | 1280 | 100% |

The calibration results indicated a consistent inverse relationship between analog readings and soil moisture content. As the water content increased, the analog output decreased due to changes in the dielectric properties of the soil detected by the capacitive sensor. This behavior is consistent with the operating principle of capacitive soil moisture sensors.

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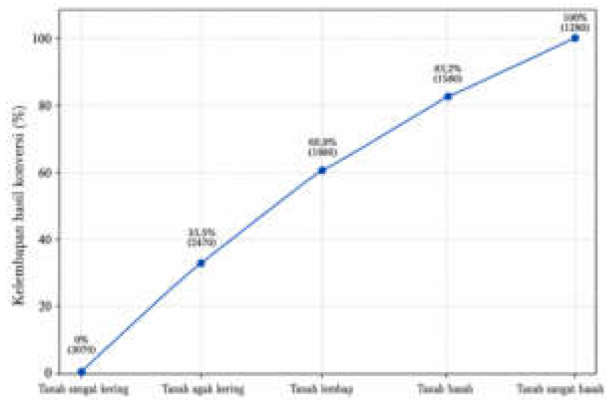


Figure 2. Calibration Curve of the Capacitive Soil Moisture Sensor

Although satisfactory calibration results were achieved, the calibration equation is applicable only to the humus soil used in this study. Different soil types, such as sandy soil, clay, or mixed growing media, possess different dielectric characteristics; therefore, recalibration is required before practical implementation under different environmental conditions.

**Sensor Accuracy Evaluation**

Sensor accuracy was evaluated by comparing the measured soil moisture values with those obtained from a commercial soil moisture meter under ten different moisture conditions. The experimental results revealed an average measurement error of 3.42%, with the highest error reaching 4.44% and the lowest error being 2.50%.

Table 2. Soil Moisture Sensor Accuracy Evaluation Results

| No. | Reference Value (%) | System Value (%) | Difference (%) | Error (%) |
|---|---|---|---|---|
| 1 | 28 | 27 | 1 | 3.57 |
| 2 | 32 | 31 | 1 | 3.13 |
| 3 | 36 | 35 | 1 | 2.78 |
| 4 | 40 | 39 | 1 | 2.50 |
| 5 | 45 | 43 | 2 | 4.44 |
| 6 | 50 | 48 | 2 | 4.00 |
| 7 | 55 | 53 | 2 | 3.64 |
| 8 | 60 | 58 | 2 | 3.33 |
| 9 | 65 | 63 | 2 | 3.08 |
| 10 | 70 | 68 | 2 | 2.86 |

The relatively low measurement error indicates that the capacitive soil moisture sensor provides sufficient accuracy for automatic irrigation applications. Minor discrepancies between sensor measurements and the reference instrument may result from soil density variation, uneven water distribution within the soil, sensor placement, and inherent measurement uncertainty of the reference instrument.

Compared with previous studies employing low-cost capacitive soil moisture sensors, the obtained error percentage falls within an acceptable range, confirming that the sensor is suitable for real-time irrigation control systems.

**Automatic Water Pump Control Performance**

The irrigation control mechanism was evaluated to determine its capability to maintain soil moisture within the predefined operating range. Experimental results showed that the water pump consistently activated whenever soil moisture decreased below 40% and automatically stopped once the moisture level reached approximately 60%.

Table 3. Automatic Water Pump Control Performance Evaluation Results

| No. | Initial Soil Moisture (%) | Pump Status | Final Soil Moisture (%) | Pump Operating Time (s) | Result |
|---|---|---|---|---|---|
| 1 | 38 | ON | 60 | 42 | Successful |
| 2 | 37 | ON | 61 | 45 | Successful |
| 3 | 39 | ON | 60 | 39 | Successful |
| 4 | 35 | ON | 60 | 51 | Successful |
| 5 | 34 | ON | 62 | 55 | Successful |
| 6 | 41 | OFF | 41 | 0 | Successful |
| 7 | 58 | OFF | 58 | 0 | Successful |
| 8 | 62 | OFF | 62 | 0 | Successful |

The implementation of two moisture thresholds represents a hysteresis control strategy, which effectively minimizes repetitive ON–OFF switching around the threshold values. Consequently, relay operation becomes more stable while reducing mechanical wear on both the relay and the water pump.

Furthermore, the irrigation duration depended on the initial soil moisture condition. Drier soil required a longer irrigation period before reaching the upper moisture threshold, whereas moderately moist soil required only a short irrigation duration.

**System Response Time**

The system response time was evaluated through ten experimental trials. The average response time required for the system to detect dry soil conditions and activate the water pump was approximately 2.14 seconds.

This response time demonstrates that the developed system is capable of responding rapidly to changes in soil moisture conditions. The slight delay observed during testing mainly originated from sensor sampling intervals, data processing performed by the ESP32, and communication between the ESP32 and the Blynk cloud server.

Table 4. Response Time Evaluation of the Automatic Irrigation System

| No. | Soil Moisture Condition | Pump Status | Response Time (s) |
|---|---|---|---|
| 1 | < 40% | ON | 2.1 |
| 2 | < 40% | ON | 2.0 |
| 3 | < 40% | ON | 2.3 |
| 4 | < 40% | ON | 2.2 |
| 5 | < 40% | ON | 2.1 |
| 6 | < 40% | ON | 2.4 |
| 7 | < 40% | ON | 2.0 |
| 8 | < 40% | ON | 2.2 |
| 9 | < 40% | ON | 2.1 |
| 10 | < 40% | ON | 2.0 |

Considering that soil moisture changes occur relatively slowly in agricultural environments, a response time of approximately two seconds is considered sufficiently fast for practical irrigation applications.

**IoT-Based Monitoring Performance**

The developed IoT platform successfully transmitted all monitoring data to the Blynk application in real time while maintaining stable Wi-Fi connectivity. The application displayed soil moisture values in both numerical and graphical formats and provided real-time information regarding the operating status of the irrigation pump.

During periods of weak Wi-Fi signal strength, data synchronization experienced delays ranging from 4 to 6 seconds. Nevertheless, these communication delays did not affect irrigation performance because all control decisions were executed locally by the ESP32 microcontroller. Consequently, the irrigation system continued operating autonomously even during temporary network interruptions.

**Seven-Day System Performance Evaluation**

A seven-day continuous evaluation was conducted using humus soil as the planting medium. Throughout the observation period, the average daily soil moisture remained within the range of 50.9%–54.2%, while the minimum and maximum recorded moisture values were 35% and 63%, respectively.

Table 5. Summary of System Performance Evaluation Over a Seven-Day Testing Period

| Day | Average Soil Moisture (%) | Minimum Soil Moisture (%) | Maximum Soil Moisture (%) | Pump Activations (times) | Automatic Water Consumption (mL) |
|---|---|---|---|---|---|
| 1 | 52.4 | 38 | 61 | 2 | 620 |
| 2 | 53.1 | 39 | 62 | 2 | 590 |
| 3 | 51.8 | 36 | 60 | 3 | 760 |
| 4 | 54.2 | 40 | 63 | 1 | 410 |
| 5 | 52.7 | 37 | 61 | 2 | 640 |
| 6 | 50.9 | 35 | 60 | 3 | 790 |
| 7 | 53.6 | 39 | 62 | 2 | 610 |

These results demonstrate that the proposed irrigation system effectively maintained soil moisture within the desired operating range. Depending on environmental conditions, the irrigation pump operated between one and three times per day. This variation indicates that the developed system performs adaptive irrigation based on actual soil conditions rather than relying on predetermined irrigation schedules

**Water Consumption Analysis**

The efficiency of the developed irrigation system was evaluated by comparing its water consumption with conventional manual irrigation. During the seven-day experimental period, manual irrigation consumed 6300 mL of water, whereas the proposed automatic irrigation system required only 4420 mL, resulting in a water saving of 1880 mL, equivalent to approximately 31.6%.

Table 6. Comparison of Water Consumption Between Manual and Automatic Irrigation

| Day | Manual Water Consumption (mL) | Automatic Water Consumption (mL) | Water Savings (mL) |
|---|---|---|---|
| 1 | 900 | 620 | 280 |
| 2 | 900 | 590 | 310 |
| 3 | 900 | 760 | 140 |
| 4 | 900 | 410 | 490 |
| 5 | 900 | 640 | 260 |
| 6 | 900 | 790 | 110 |
| 7 | 900 | 610 | 290 |
| **Total** | **6300** | **4420** | **1880** |

The observed reduction in water consumption demonstrates that soil moisture-based irrigation effectively prevents unnecessary watering. In manual irrigation, watering is typically performed according to fixed schedules regardless of actual soil moisture conditions. Conversely, the proposed system activates irrigation only when soil moisture falls below the predefined threshold, thereby significantly improving water-use efficiency.

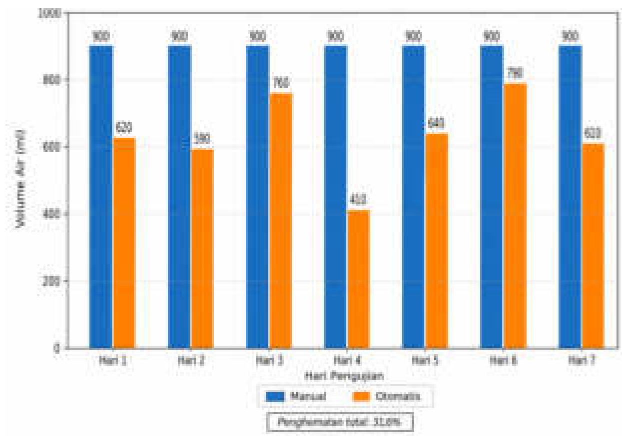


Figure 3. Comparison of Water Consumption Between Manual and Automatic Irrigation

These findings suggest that IoT-based automatic irrigation systems have considerable potential to support sustainable water management, particularly in small-scale agriculture, home gardening, and greenhouse cultivation.

**Discussion**

The experimental results confirm that integrating the ESP32 microcontroller, capacitive soil moisture sensor, relay module, and Blynk platform provides an effective solution for real-time soil moisture monitoring and automatic irrigation control. The average sensor error of 3.42%, average response time of 2.14 seconds, and water-saving performance of 31.6% demonstrate that the proposed system successfully achieved the research objectives.

Compared with previous studies, which primarily emphasized system implementation and IoT communication, this research provides a more comprehensive evaluation by assessing sensor calibration, measurement accuracy, response time, hysteresis-based control stability, and irrigation efficiency. Such comprehensive performance evaluation provides stronger evidence regarding the effectiveness of the developed system.

Despite these promising results, several limitations should be acknowledged. The experimental evaluation was conducted using only one soil type and a single soil moisture sensor, limiting the generalizability of the findings to larger agricultural fields. Moreover, the monitoring system depends on Wi-Fi connectivity for remote access, making Internet availability an important operational requirement.

Future studies should investigate the integration of multiple soil moisture sensors, environmental sensors (temperature, humidity, solar radiation, and rainfall), cloud-based data analytics, and Artificial Intelligence (AI) or Machine Learning (ML) techniques to predict irrigation requirements based on environmental conditions and crop growth patterns. Such enhancements are expected to further improve irrigation efficiency and support precision agriculture applications.

## CONCLUSION

This study successfully designed and implemented an Internet of Things (IoT)-based soil moisture monitoring and automatic irrigation system using an ESP32 microcontroller, a capacitive soil moisture sensor, a relay module, a 12 V DC water pump, and the Blynk platform for real-time monitoring. The developed system was capable of continuously monitoring soil moisture, automatically controlling irrigation based on predefined soil moisture thresholds, and providing remote monitoring through an Internet-connected mobile application. Experimental results demonstrated that the proposed system achieved satisfactory performance, with an average sensor measurement error of 3.42%, an average response time of 2.14 seconds, and stable soil moisture maintenance within the desired operating range. The implementation of a hysteresis control strategy significantly improved pump operation stability by preventing excessive ON–OFF switching around the threshold values. Furthermore, the proposed system reduced water consumption by 31.6% compared with conventional manual irrigation, indicating its effectiveness in improving irrigation efficiency while supporting sustainable water management. These findings demonstrate that the developed IoT-based irrigation system is suitable for small-scale agricultural applications, home gardens, potted plants, and greenhouse environments requiring real-time monitoring and automatic irrigation control. Despite its promising performance, this study has several limitations. The experimental evaluation was conducted using a single soil type and a single soil moisture sensor under controlled conditions, which may limit the generalizability of the findings to larger agricultural environments. Future research should investigate the integration of multiple soil moisture sensors, additional environmental sensors (e.g., temperature, humidity, rainfall, and solar radiation), cloud-based data analytics, and Artificial Intelligence (AI) or Machine Learning (ML) techniques to enable predictive irrigation management and improve the adaptability of smart irrigation systems under diverse environmental conditions.

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