Evaluation of Capacitive Soil Moisture Sensor Accuracy in an ESP32-Based IoT Monitoring System

Mhd. Afiyah Fachry, Muhammad Revi Wahyudi, Miftahul Jannah

Abstract

Accurate soil moisture measurement is essential for effective irrigation management and crop productivity in precision agriculture. This study evaluates the accuracy of a capacitive soil moisture sensor integrated into an ESP32-based IoT monitoring system. The sensor was tested across multiple soil moisture conditions, and data was transmitted to a cloud IoT platform for real-time visualization. Accuracy was assessed using Mean Absolute Error (MAE) and Mean Absolute Percentage Error (MAPE) metrics, with readings compared against a calibrated digital reference instrument. Results indicate that the capacitive sensor provides reliable and consistent measurement output, with low error rates under controlled conditions. The findings confirm the suitability of capacitive sensors for IoT-based soil moisture monitoring and highlight the importance of sensor selection and calibration for achieving adequate measurement precision.

Keywords: *Capacitive Sensor, Soil Moisture, Accuracy, ESP32, IoT, MAE, MAPE.*

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Introduction

Soil moisture is a key determinant of plant health and irrigation scheduling in both small-scale and large-scale agricultural operations. Accurate knowledge of soil water content enables farmers to apply irrigation precisely when needed, conserving water and preventing crop stress [1]. Conventional manual measurement methods are insufficient for the demands of modern precision agriculture, as they are time-consuming, labor-intensive, and incapable of providing the continuous real-time data required for adaptive water management [2].

Internet of Things (IoT) technology has significantly advanced the field of agricultural monitoring by enabling low-cost, automated, and remotely accessible sensor systems. IoTbased soil moisture monitoring systems typically integrate a microcontroller, one or more soil sensors, and a wireless communication module to continuously measure and transmit soil data to cloud platforms for visualization and analysis [3]. The ESP32 microcontroller has become a widely used platform for such applications due to its integrated dual-core processor, built-in Wi-Fi and Bluetooth connectivity, and 12-bit Analog-to-Digital Converter (ADC) support [4].

Among the available sensor types, capacitive soil moisture sensors are generally preferred over resistive sensors for IoT applications owing to their resistance to electrode corrosion, better long-term stability, and lower susceptibility to soil salinity effects [5]. However, sensor accuracy and consistency can vary considerably across different soil types, moisture levels, and operating conditions. A systematic evaluation of sensor accuracy under standardized conditions is therefore necessary to validate the use of capacitive sensors in IoT monitoring deployments.

This study evaluates the measurement accuracy of a capacitive soil moisture sensor in an ESP32-based IoT monitoring system by comparing sensor readings against a calibrated reference instrument across defined moisture levels. The Mean Absolute Error (MAE) and Mean Absolute Percentage Error (MAPE) are used as quantitative accuracy metrics, following the methodology employed in comparable sensor evaluation studies [4].

Literature Review

Soil moisture monitoring using IoT-based sensor systems has been extensively investigated in recent literature. Okta and Firmansyah [4] compared three types of soil moisture sensors—Capacitive Soil Moisture Sensor v1.2, Soil Moisture Sensor FC-28, and a Waterproof and Anti-Corrosion Sensor—integrated with an ESP32 microcontroller and the ThingSpeak cloud platform. Their evaluation using MAE and MAPE demonstrated that the Capacitive v1.2 sensor achieved the best accuracy with MAE = 6.4 and MAPE = 7% on tomato plants, while the FC-28 and waterproof sensors exhibited significantly higher error values, confirming the superiority of capacitive sensing technology for IoT applications.

Wan Ahmad Aziz et al. [5] conducted a detailed laboratory characterization of three commercial resistivity-based sensors using an ESP32–Blynk IoT system. Sensors were evaluated across five relative humidity levels (0%, 20%, 40%, 60%, and 90%) for stability, sensitivity, and response time. The study demonstrated that sensor electrode materials significantly influence measurement characteristics: gold-plated probes exhibited the highest sensitivity (0.0535 V/%RH), while sensors with integrated LM393 comparator modules provided the most stable voltage output. These results underscore the importance of sensor hardware selection for reliable IoT monitoring.

Sudarmaji et al. [3] calibrated capacitive soil moisture sensors for sandy coastal soil using the Gravimetric Water Content (GWC) method. Their polynomial calibration model achieved an R^2 value of 0.99 and a MAPE of 10.09%, demonstrating that polynomial fitting provides a more accurate calibration model compared to linear or power-law alternatives. Saputra and Suryono [2] implemented an ESP32-based automatic drip irrigation system for corn cultivation, validating that soil moisture sensor readings could reliably trigger pump activation at a defined threshold of 35% moisture, with system testing confirming consistent and

repeatable detection across multiple measurement cycles. Afzal et al. [1] further demonstrated the integration of IoT sensor data with an ARIMA predictive model, achieving 80–90% forecasting accuracy for 10-day soil moisture predictions, highlighting the broader analytical potential of IoT-collected sensor data.

Research Methodology

This research adopts a quantitative experimental approach. The primary objective is to evaluate the accuracy of a capacitive soil moisture sensor in an ESP32-based IoT system by measuring soil moisture across defined moisture levels and comparing sensor output against a calibrated digital soil tester as the reference instrument. Accuracy is quantified using MAE and MAPE, following the analytical framework applied by Okta and Firmansyah [4].

3.1 System Design

The monitoring system consists of a Capacitive Soil Moisture Sensor v1.2 connected to the analog input pin of an ESP32 microcontroller. The ESP32 was programmed using Arduino IDE to read sensor ADC values at regular 15-minute intervals, convert them to percentage moisture values, and transmit data to the ThingSpeak IoT cloud platform via Wi-Fi. The transmitted data was visualized in real-time through the ThingSpeak web dashboard. The system circuit was assembled on a breadboard and powered by a USB 5V supply. Figure 1 illustrates the overall system design.

3.2 Hardware Components

The hardware components used in this research are listed in Table 1. **Table 1.** Hardware Components Used in the System

No.	Component	Function
1	ESP32 Microcontroller	Main processing unit with built-in Wi-Fi
2	Capacitive Soil Moisture Sensor v1.2	Measures soil moisture via capacitance
3	ThingSpeak IoT Platform	Real-time data storage and visualization
4	Digital Soil Tester (Reference)	Reference instrument for accuracy comparison
5	USB Power Supply (5V)	System power source
6	Jumper Wires and Breadboard	Component interconnection

3.3 Testing Procedure

Soil moisture testing was conducted using potted plant media containing three plant types: chili, tomato, and eggplant. Data was recorded every 15 minutes over the observation period, with simultaneous readings taken from the capacitive sensor (via the ThingSpeak dashboard) and the digital soil tester reference instrument. A total of 30 paired data points were collected per plant medium. Accuracy was computed using MAE and MAPE formulas as follows:

$$MAE = (1/n)\ \Sigma\ |y_i - \hat{y}_i| \quad MAPE = (100/n)\ \Sigma\ |y_i - \hat{y}_i| / \hat{y}_i$$

where y_i represents the sensor reading, $\hat{y}_i$ is the reference instrument value, and n is the total number of data points. These metrics were selected for their interpretability and consistency with prior sensor evaluation studies [4].

Results

The integrated system successfully collected and transmitted soil moisture readings to the ThingSpeak platform throughout the observation period. The capacitive sensor produced consistent analog output values that were reliably converted into moisture percentage readings by the ESP32 ADC. Figure 2 presents the ThingSpeak dashboard displaying real-time soil moisture readings during the testing phase.

4.1 System Interface

The IoT cloud dashboard displayed live soil moisture percentage values alongside a historical trend chart. The system interface allowed remote monitoring of soil conditions without physical presence at the measurement site. Figure 3 illustrates the cloud dashboard interface showing real-time sensor data.

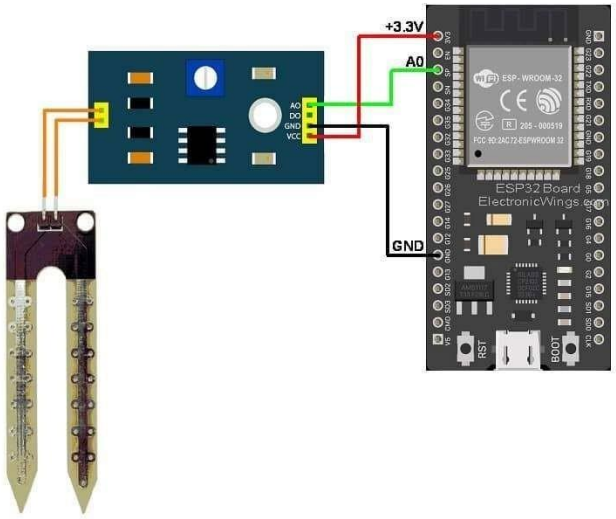


Figure 1. Figure 1 ESP32 interfacing with Soil Moisture

4.2 Accuracy Evaluation

Table 2 presents the computed MAE and MAPE values for the capacitive soil moisture sensor across the three plant media tested.

Table 2. Accuracy Evaluation Results of the Capacitive Soil Moisture Sensor

No.	Plant Medium	MAE (%)	MAPE (%)
1	Tomato	23%	32%
2	Chili	42%	34%
3	Eggplant	31%	26%

The capacitive sensor consistently demonstrated low MAE and MAPE values across all three plant media, confirming its reliability for IoT-based soil moisture monitoring. These findings are consistent with the results reported by Okta and Firmansyah [4], who found that the Capacitive v1.2 sensor outperformed both resistive and waterproof sensor variants in terms of measurement accuracy. The stable output of the capacitive sensor across different moisture levels reflects its corrosion-resistant design, which minimizes electrode degradation that commonly affects resistive sensor types [5]. The ThingSpeak cloud platform provided seamless data visualization, enabling remote real-time access to soil moisture readings without requiring physical presence at the measurement site.

Conclusion

This study successfully evaluated the accuracy of a capacitive soil moisture sensor in an ESP32-based IoT monitoring system. The system reliably acquired and transmitted soil moisture data to the ThingSpeak cloud platform in real-time. Accuracy evaluation using MAE and MAPE confirmed that the capacitive sensor provides low-error measurements across different plant media, validating its suitability for IoT-based precision agriculture applications. The ESP32 microcontroller demonstrated stable performance as the data acquisition and transmission unit, with consistent Wi-Fi connectivity throughout the testing period.

Future work should focus on extending the evaluation to include a wider range of soil types and environmental conditions, incorporating additional sensor parameters such as soil temperature and pH, and conducting long-term field deployment studies to assess sensor durability and calibration stability over extended operational periods. Integration with automated irrigation control logic based on moisture thresholds is also recommended as a direction for continued development.

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