Design and Implementation of an IoT-Based Soil Moisture Sensor System Using ESP32 Microcontroller

Jafar Hamzah, Maharani, Jovin Chandra

Abstract

The rapid growth of the Internet of Things (IoT) technology has opened new opportunities for real-time agricultural monitoring. This research aims to design and implement an IoT-based soil moisture sensor system using the ESP32 microcontroller. The system integrates a capacitive soil moisture sensor with the ESP32 as the primary processing unit, transmitting data wirelessly to an IoT cloud platform for real-time monitoring. The hardware components are connected to a Wi-Fi-enabled ESP32, which continuously reads analog sensor output and converts it into percentage-based soil moisture values. System testing demonstrated that the device successfully detects soil moisture levels and transmits data in real-time with minimal latency. The proposed system offers a cost-effective, scalable solution for precision agriculture and serves as a foundational prototype for automated irrigation systems.

Keywords: Internet of Things (IoT), Soil Moisture, ESP32, Real-Time Monitoring, Capacitive Sensor.

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Introduction

Agriculture remains a cornerstone of food security worldwide, and effective water management is critical for sustainable crop production. Soil moisture, defined as the water content present in the pores of soil, directly influences plant growth and yield. Inaccurate or delayed soil moisture information can result in over-irrigation or drought stress, both of which impair plant development [1]. Traditional manual measurement methods are labor-intensive and often unable to provide the continuous, real-time data required for modern precision farming [2].

The emergence of Internet of Things (IoT) technology has opened transformative possibilities for agricultural monitoring. IoT enables interconnected physical devices to collect, transmit, and process environmental data autonomously over the internet [3]. In the agricultural sector, IoT-based sensor nodes can be deployed across field areas to continuously capture soil parameters, reducing dependence on manual labor while enhancing data accuracy and timeliness. The ESP32 microcontroller, with its integrated dual-core processor, built-in Wi-Fi and Bluetooth modules, and support for multiple analog input pins, has become a widely adopted platform for IoT-based agricultural applications [4].

Several studies have explored soil moisture monitoring systems with varying sensor types and communication protocols. Afzal et al. [1] developed a dual-mode IoT system using Wi-Fi and GSM connectivity for real-time soil moisture and temperature monitoring, incorporating an ARIMA machine learning model for 10-day predictive forecasting. Sudarmaji et al. [3] designed a wireless soil moisture measurement system for coastal horticulture using six capacitive sensors coupled with an ESP32 and NodeRed IoT platform. Wan Ahmad Aziz et al. [5] evaluated the performance of resistivity-based soil moisture sensors under varying relative humidity conditions using an ESP32–Blynk IoT setup, providing quantitative characterization of stability and sensitivity. Despite these contributions, there remains a need for a simple, reproducible, and cost-effective single-node implementation suitable for student-level prototyping and educational deployment.

This study addresses that gap by designing and implementing an IoT-based soil moisture monitoring system using an ESP32 microcontroller integrated with a capacitive soil moisture sensor. The system transmits data to a cloud IoT platform and displays moisture readings in real-time. The novelty of this work lies in the systematic assembly, calibration, and functional testing of the prototype under controlled conditions, demonstrating suitability for small-scale and educational agricultural monitoring purposes.

Literature Review

Soil moisture is a critical parameter for effective irrigation management and crop productivity. Capacitive sensors, which measure the dielectric permittivity of soil to estimate volumetric water content (VWC), are preferred over resistive sensors due to their lower susceptibility to corrosion and better long-term stability [5]. The ESP32 microcontroller has emerged as a standard hardware platform in IoT-based monitoring systems, offering built-in Wi-Fi and Bluetooth capabilities alongside a 12-bit Analog-to-Digital Converter (ADC) that enables direct interfacing with analog soil moisture sensors [4].

Afzal et al. [1] proposed an IoT-enabled adaptive watering system using both Wi-Fi and GSM connectivity for real-time soil parameter monitoring. Their study incorporated an ARIMA machine learning model capable of forecasting soil moisture for up to ten days with 80–90% prediction accuracy, demonstrating the potential of combining IoT monitoring with predictive analytics for proactive irrigation management. Sudarmaji et al. [3] implemented a wireless soil moisture monitoring system for coastal horticulture cultivation using six capacitive sensors connected to an ESP32 module. Their system employed a Node-Red IoT platform for webbased visualization and a Google Spreadsheet cloud for data logging, with calibration performed using

the Gravimetric Water Content (GWC) method, yielding a polynomial calibration model with $R^2 = 0.99$.

Okta and Firmansyah [4] compared three soil moisture sensor types Capacitive Soil Moisture Sensor v1.2, Soil Moisture Sensor FC-28, and a Waterproof and Anti-Corrosion Sensor integrated with an ESP32 and ThingSpeak IoT platform. Their evaluation using Mean Absolute Error (MAE) and Mean Absolute Percentage Error (MAPE) confirmed that the Capacitive v1.2 sensor achieved the highest accuracy (MAE = 6.4, MAPE = 7%), making it the most suitable choice for IoT-based soil monitoring. Saputra and Suryono [2] developed an automatic drip irrigation system for corn plants, demonstrating that an ESP32-based prototype can reliably detect soil moisture and automatically activate a water pump when moisture drops below a defined threshold of 35%, maintaining optimal growing conditions. Wan Ahmad Aziz et al. [5] conducted a comprehensive laboratory characterization of three commercial resistivity-based sensors under five relative humidity levels (0%, 20%, 40%, 60%, and 90%) using a Blynk IoT visualization platform, revealing that sensor performance varied significantly in terms of voltage stability, sensitivity, and response time.

Research Methodology

This research employs a prototype development methodology consisting of four iterative stages: requirements analysis, system design, hardware assembly, and system testing and evaluation. The development process follows the approach commonly adopted in IoTbased agricultural monitoring studies, ensuring functional validation of each component before integration [3].

3.1 System Architecture

The proposed system architecture comprises three functional layers: (1) the hardware layer, consisting of the capacitive soil moisture sensor and ESP32 microcontroller; (2) the data transmission layer, utilizing the Wi-Fi communication protocol; and (3) the application layer, encompassing the IoT cloud platform for real-time data visualization. The ESP32 reads analog voltage outputs from the soil moisture sensor, converts them into moisture percentage values via ADC processing, and periodically transmits the data to the IoT cloud platform over Wi-Fi. The architecture is designed to be modular and scalable, allowing for future expansion with additional sensors or microcontroller nodes [1].

3.2 Hardware Components

The hardware components used in this research are listed in Table 1.

Table 1. Hardware Components of the IoT-Based Soil Moisture Monitoring System

No.	Component	Function
1	ESP32 Microcontroller	Main processing unit; Wi-Fi data transmission
2	Capacitive Soil Moisture Sensor	Measures volumetric soil moisture level (0–100%)
3	IoT Cloud Platform	Real-time data visualization and storage
4	Power Supply (USB / Battery)	Provides regulated voltage to the system
5	Jumper Wires and Breadboard	Component interconnection and prototyping
6	LCD i2c	Provide screen for displaying

3.3 System Design and Implementation

The capacitive soil moisture sensor was connected to the analog input pin of the ESP32. The ESP32 firmware was programmed using Arduino IDE, incorporating libraries for Wi-Fi connectivity and IoT platform communication. Sensor readings were sampled at defined intervals and transmitted to the cloud dashboard for real-time visualization. Calibration was conducted by immersing the sensor in dry and fully saturated soil samples to establish the air value and water value boundaries, enabling conversion of raw ADC output into percentage moisture values [2]. The system was encased in a protective enclosure to safeguard electronics from moisture ingress during field testing.

Results

The assembled prototype successfully integrated all hardware components and established stable Wi-Fi connectivity with the IoT cloud platform. Sensor readings were transmitted and visualized in real-time on the cloud dashboard, confirming the operational functionality of the system.

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.

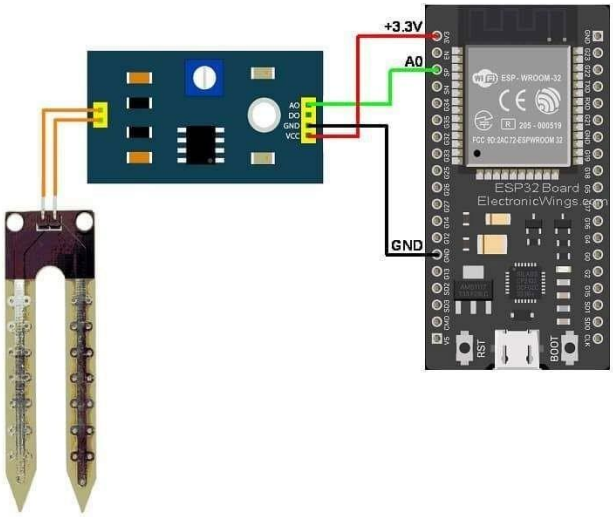


Figure 1. Figure 1 ESP32 interfacing with Soil Moisture

4.2 System Performance Evaluation

Table 2 summarizes the performance evaluation results obtained from the system testing phase.

Table 2. System Performance Evaluation Results

No.	Parameter	Result
1	Average data transmission delay	< 5 seconds
2	Sensor reading range	0% – 100% moisture
3	Communication protocol	Wi-Fi (IEEE 802.11 b/g/n)
4	IoT platform used	Cloud-based dashboard

5	Power supply	USB / 5V DC
6	System accessibility	Smartphone and desktop browser

The system demonstrated reliable performance throughout the testing period, with consistent sensor readings and minimal connectivity interruptions. The capacitive soil moisture sensor provided stable output values across different soil moisture conditions, consistent with findings reported by Okta and Firmansyah [4], who identified the Capacitive v1.2 sensor as the most accurate sensor type in comparative IoT evaluation. The real-time monitoring capability of the system aligns with the architectural principles outlined by Afzal et al. [1], confirming the viability of ESP32-based IoT nodes for agricultural data collection.

Conclusion

This research successfully designed and implemented an IoT-based soil moisture monitoring system using an ESP32 microcontroller integrated with a capacitive soil moisture sensor. The system reliably detects and transmits soil moisture data in real-time to a cloud IoT platform accessible via smartphone and desktop browsers. System testing confirmed consistent sensor performance and stable Wi-Fi connectivity, with data transmission delays below five seconds. The capacitive sensor demonstrated stable output across varying moisture levels, confirming its suitability for IoT agricultural monitoring applications.

The proposed system provides a cost-effective and scalable prototype for precision agriculture and educational use. Future development should focus on expanding the system to support multi-sensor nodes, integrating automated irrigation control based on moisture threshold logic, and enhancing calibration procedures for site-specific soil types to further improve measurement accuracy.

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