



# **Development of an IoT-Enabled *In-situ* Soil Monitoring System for Enhancing Precision in Agricultural Practices**

**Jelili Aremu Oyedokun <sup>a,b</sup>, Muniru Olajide Okelola <sup>a</sup>,  
Elijah Olusayo Omidiora <sup>c</sup>, Wasiu Babatunde Akanbi <sup>d</sup>  
and Olusayo Adekunle Ajeigbe <sup>e\*</sup>**

<sup>a</sup> Department of Electronic and Electrical Engineering, Faculty of Engineering and Technology,  
Ladoke Akintola University of Technology, Ogbomoso, Nigeria.

<sup>b</sup> Engineering and Scientific Services Department, National Centre for Agricultural Mechanization,  
Ilorin, Nigeria.

<sup>c</sup> Department of Computer Engineering, Faculty of Engineering and Technology, Ladoke Akintola  
University of Technology, Ogbomoso, Nigeria.

<sup>d</sup> Department of Crop Production and Soil Science, Faculty of Agricultural Science, Ladoke Akintola  
University of Technology, Ogbomoso, Nigeria.

<sup>e</sup> Department of Electrical and Electronics Engineering, Faculty of Engineering, Ajayi Crowther  
University, Oyo, Nigeria.

## **Authors' contributions**

*This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.*

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\*Corresponding author: Email: [oa.ajeigbe@acu.edu.ng](mailto:oa.ajeigbe@acu.edu.ng);

## ABSTRACT

The increasing global demand for food production necessitates the adoption of advanced technologies to optimize agricultural practices. This paper focuses on the development of an Internet of Things (IoT)-enabled in-situ soil monitoring system designed to enhance precision agriculture. The system includes a network of high-tech soil sensors that can measure important soil parameters like moisture, temperature, pH, electrical conductivity (EC), and levels of key nutrients (nitrogen, phosphorus, and potassium). These parameters are continuously monitored in real-time and transmitted to a cloud-based platform for secure data storage. The system provides farmers with actionable insights into soil health and nutrient status, enabling data-driven decision-making for efficient irrigation, fertilization, and crop management. By leveraging IoT technology, this approach enhances resource utilization, improves agricultural productivity, and promotes sustainable farming practices. The implementation of this system has the potential to optimize crop yields while minimizing environmental impact, contributing to the advancement of smart agriculture and global food security.

**Keywords:** *Development; internet of things; In-situ soil monitoring system; precision; agricultural practices.*

## 1. INTRODUCTION

Soil quality is a key determinant of agricultural productivity, directly impacting crop yield, nutrient availability, and overall plant health. Soil quality plays a crucial role in determining agricultural productivity, influencing crop yield, nutrient availability, and overall plant health (Saikia et al., 2025; Saha et al., 2021). Traditional soil monitoring methods, which depend on periodic manual sampling and laboratory analysis, are often labor-intensive, time-consuming, and costly. Additionally, these conventional approaches lack the capability to provide real-time insights into soil conditions, making it difficult for farmers to make timely, data-driven decisions regarding irrigation, fertilization, and soil management (Chamara et al., 2022). The integration of Internet of Things (IoT) and smart sensing technologies presents a transformative solution to these challenges by enabling continuous, real-time monitoring of critical soil parameters. IoT-based automation systems play a vital role in improving farm management and optimizing agricultural practices (Katiyar and Farhana, 2021). The pursuit of sustainable agriculture has heightened the demand for effective and immediate solutions for fertilizer application management, as inadequate nutrient management results in detrimental environmental consequences, including soil contamination and water pollution (NIAST, 2023). Modern agriculture progressively integrates technological advancements to improve efficiency and productivity (Karar et al., 2021). IoT technology amalgamates diverse devices and sensors for instantaneous communication.

IoT technology integrates various devices and sensors to enable real-time communication (Saikat et al., 2021). These technologies enable farmers to monitor and regulate environmental parameters such as temperature, humidity, and soil conditions with enhanced precision and efficacy—greater precision and efficiency. These technologies also improve our understanding of how agriculture works and allow for the use of smart solutions like automated irrigation, better planting schedules, and efficient resource management (Fernández-Ahumada et al., 2019).

This technology enhances agriculture's adaptability, responsiveness, and sustainability, effectively tackling modern agricultural difficulties through new and pragmatic methods. The IoT technology facilitates real-time data acquisition from dispersed sensors throughout agricultural land, yielding critical insights for enhanced decision-making precision. The integration of this technology improves agricultural environmental monitoring and diminishes dependence on extensive human oversight (Saad et al., 2020).

IoT-based automation enables farmers to adjust to alterations in agricultural circumstances remotely. This method conserves time and diminishes the human effort required for traditional monitoring. The process saves time and reduces the need for manual monitoring. Sensors and automation devices oversee daily operations, deliver real-time updates, and autonomously execute corrective measures. As a result, farmers can optimize their time and resources, concentrate on tasks necessitating human involvement, and improve overall

agricultural productivity (Wakchaure et al., 2020). The use of agricultural technology enhances management and provides farmers with increased autonomy and adaptability in their operations (Abebe et al., 2023).

The calibration process is essential for ensuring that sensors deliver precise and quantifiable data, particularly in the presence of intricate environmental fluctuations (Montoya et al., 2020). Accurate calibration ensures the precision of soil parameter measurements, which are vital for assessing soil conditions. Sensor validation guarantees data dependability and assesses if sensors yield consistent results with actual field conditions (Muthmainnah et al., 2023; Chaganti et al., 2022). However, the prior art discloses some advanced features that remain inaccessible to small-scale farmers due to high costs and the need for complex processes like chemical analysis and spectroscopy. The prior art provides some improvements by integrating spectral analysis to detect macronutrients, but this system lacks portability and real-time feedback. Another notable device outlined uses AI-3-driven analysis but is limited by its inability to adapt to different manure types and environmental conditions (Ferrag et al., 2021).

This research produces precise and trustworthy data by carefully adjusting and checking the equipment, which helps us understand farming and environmental conditions better while enhancing sensor technology for soil moisture, temperature, electrical conductivity, hydrogen percentage, and macronutrients (nitrogen, phosphorus, and potassium) in smart agriculture.

This research aims to design, implement, and calibrate an IoT-enabled soil monitoring system for precise, real-time soil analysis. By integrating connected sensors with an IoT platform, the system will provide farmers with detailed, data-driven insights to optimize soil health management and crop productivity. The study focuses on sensor calibration and validation to ensure accuracy and reliability under real-field conditions, bridging the gap between traditional soil analysis methods and modern digital agriculture. The expected outcomes include a scalable, cost-effective solution suitable for both smallholder and commercial farmers that enhances precision farming practices. In the end, this research helps improve farming technology by allowing for automatic soil checks, cutting

down on wasted resources, and encouraging sustainable farming practices.

In the subsequent sections, this paper explains the system design, how sensors were chosen, the methods for calibration, the ways data is sent, and the process used to check how well the proposed soil monitoring system works.

## **2. MATERIALS AND METHODS**

### **2.1 Materials**

The system involved both the software and hardware components. the software involved is the C++ programming written for the system, while the hardware components involved are the ESP32 microcontroller, RS485 Modbus sensor 7-in-1 sensor, MAX485 module/RS485 to RS-485 Module converter, Liquid Crystal Display (LCD), Arduino keypad, switch, Wi-Fi, and power unit. The ESP32 serves as the brain of the system; it is responsible for collecting data from the sensors, processing it, displaying it on the LCD, and saving and storing it in the cloud.

### **2.2 Description of the Components Used**

This section provides a detailed description of the components used in the development of an IoT-enabled in-situ soil monitoring system.

#### **2.2.1 ESP32 microcontroller**

The ESP32, developed by Espressif Systems, is a highly capable, low-cost microcontroller designed for energy-efficient applications, particularly in the realm of the Internet of Things (IoT), wearable technology, and mobile electronics. As the successor to the popular ESP8266, the ESP32 offers significantly improved performance and features, including integrated Wi-Fi and Bluetooth connectivity. It is built around a dual-core Xtensa® LX6 processor operating at up to 240 MHz, complemented by 512 KiB of RAM, and includes an ultra-low-power (ULP) coprocessor with 8 KiB memory designed for energy-saving operations in sleep mode. This architecture enables the ESP32 to manage high-speed processing tasks while maintaining low power consumption for background sensor monitoring. Furthermore, the ESP32 is equipped with various onboard peripherals such as ADCs, DACs, UART, SPI, I2C, PWM, and capacitive touch sensors, making it an ideal platform for standalone, connected systems. Its robust feature set, affordability, and wireless capabilities make it a reliable choice for diverse applications, including smart agriculture, home automation,

health monitoring, and industrial control systems, where real-time communication and efficient power usage are critical, as shown in Fig. 1.

## 2.2.2 RS485 Modbus 7-in-1 sensor

Power supply of 4.5 V to 30 V, operational environment of -40°C to 80°C, output RS485/4-20 mA/0-5 V/0-10 V, Temperature: measuring range -40°C to 80°C, accuracy  $\pm 5^\circ\text{C}$ , long-time stability  $\leq 0.1\%^\circ\text{C}/\text{y}$ , response time  $\leq 15$  sec. Relative humidity: measuring range 0 to 100% RH, accuracy 2% (0–50%), 3% (50–100%), long-term stability 1% RH/y, response time  $\leq 4$  sec.

Electrical conductivity: measuring range (0-20000  $\mu\text{S}/\text{cm}$ ), accuracy  $\pm 3\%$  (0-10000  $\mu\text{S}/\text{cm}$ ),  $\pm 5\%$  (10000-20000  $\mu\text{S}/\text{cm}$ ) long time stability  $\leq 1\%$   $\mu\text{S}/\text{cm}$ , response time  $\leq 1$  sec. The percentage of hydrogen has a measurement range of 3-9 pH, an accuracy of 0.3 pH, a long-term stability of 5/year, and a response time of 10 sec. Nitrogen: measuring range 1-1999 mg/kg (mg/L), resolution 1 mg/kg (mg/L), response time 1 sec. Phosphorus: measuring range 1-1999 mg/kg (mg/L), resolution 1 mg/kg (mg/L), response time 1 sec. Potassium: measuring range 1-1999 mg/kg (mg/L), resolution 1 mg/kg (mg/L), response time 1 sec. Fig. 2 displays the RS485 Modbus 7-in-1 sensor.

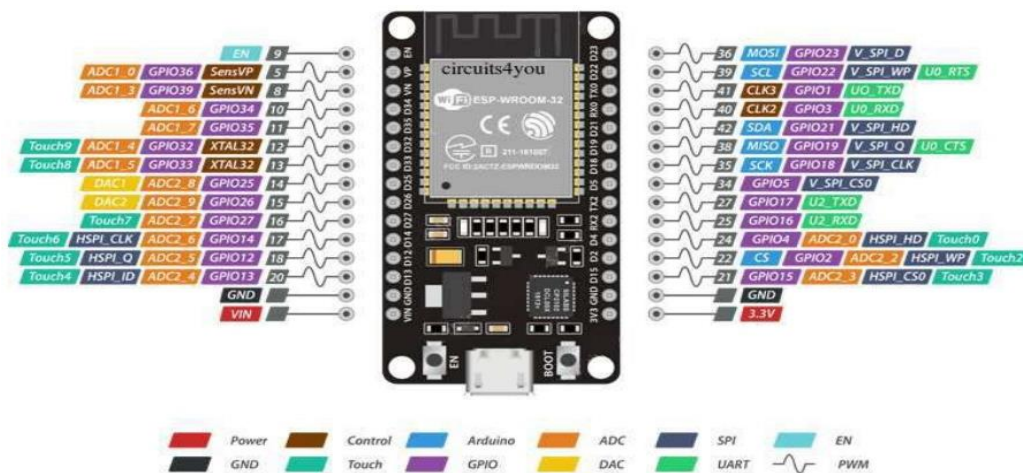


Fig. 1. ESP32 Microcontroller  
(Ramchandar et al., 2020)



Fig. 2. RS485 Modbus 4 in 1 sensor

[www.store.nerokas.co.ke/SKU-3931](http://www.store.nerokas.co.ke/SKU-3931) retrieved 7th April 7, 2025

### **2.2.3 MAX 485 module/RS485 to RS-485 module converter**

On-board MAX 485 chip, low power consumption for the RS-485 communication, slew-rate limited transceiver, 5.08 mm pitch 2P terminal, and convenient RS-485 communication wiring. The board size measures 44 mm by 14 mm and operates at 5 V.

### **2.2.4 LCD (liquid crystal display)**

An LCD2004 + 12C, 20-character, 4-line resolution, supply voltage 5 V module can be easily interfaced with MCU, low power consumption with a built-in controller.

### **2.2.5 4x4 matrix keypad module**

A 16-key membrane keyboard designed for use with microcontrollers such as Arduino, PIC, and AVR. This compact and durable plastic keypad features a matrix layout (4 rows × 4 columns), making it ideal for user input in embedded system projects.

### **2.2.6 4G LTE universal mobile MiFi internet hotspot**

Battery capacity of 3000 mAh, superfast browsing speed of up to 150 Mbps, maximum connection with 8 users, ethernet Port: 1 LAN Port with 2 times the speed, dual power options: Battery and USB power, Wi-Fi support for 2.4 GHz, and network support for 4G/3G/2G

### **2.2.7 Power unit**

The power unit comprises two 18650 lithium-ion batteries, each rated at 3800 mAh and 3.7 V, along with a charge controller to regulate charging and ensure safe and efficient power management for the system. The rechargeable batteries provide continuous power in outdoor environments, making the system suitable for deployment in rural or off-grid areas. The energy-efficient design ensures that the system operates for extended periods without frequent maintenance or battery replacement.

## **2.3 Material Acquisition**

The materials used in the construction of an IoT-enabled in-situ soil monitoring system were procured locally from reputable markets in Ilorin, Kwara State, for accessibility and immediate quality inspection. For unavailable items, international procurement was done through AliExpress. The choice of selected international orders was based on specifications, supplier ratings, reviews, and cost efficiency to meet the

required research standards. This dual-sourcing approach ensures the availability, quality, and cost-effectiveness of all necessary materials.

## **2.4 Construction Location**

The construction of the IoT-enabled in-situ soil monitoring system was carried out in the Instrumentation and Control Laboratory of the National Center for Agricultural Mechanization (NCAM) in Ilorin. This facility has been specifically selected due to its conducive environment, accessibility, and robust technical support infrastructure. These features ensure a seamless and efficient construction process, providing the necessary tools, expertise, and resources that facilitate the successful implementation of this research. The circuit diagram, block diagram, construction flow chart and working flow chart were followed strictly as shown in Figs. 3 to 6.

## **2.5 Testing and Calibration**

The developed system was tested at the NCAM Instrumentation and Control Laboratory, while its calibration was conducted in the NCAM Soil Laboratory. This facility is equipped with advanced analytical tools and specialized equipment for soil analysis and related research activities.

Calibration and rigorous evaluation of the IoT-enabled in-situ soil monitoring system were carried out in the soil laboratory, a controlled environment that ensured accuracy, reliability, and efficiency in measuring critical soil parameters. During this phase, the system's sensors and IoT components were calibrated to deliver precise and consistent readings under various conditions. The calibration process involved comparing the system's output with standard reference instruments available in the laboratory to detect and correct any deviations.

Functionality tests were also conducted to verify the system's ability to transmit real-time data seamlessly, integrate with IoT platforms, and adapt to dynamic soil conditions.

For the calibration process, a standard solution containing 1000 ppm was made for nitrogen, phosphorus, and potassium using  $\text{NH}_4\text{Cl}_2$ ,  $\text{Na}_3\text{PO}_4$ , and KCl, respectively. Electrical conductivity (EC) and pH were measured using a Hanna Instruments EC and pH meter, while a digital hygrometer was employed to monitor temperature and relative humidity.

## 2.6 The Working Principles of the Developed System

The IoT-enabled in-situ soil monitoring system works by combining advanced sensors, data collection tools, communication networks, and cloud platforms to provide immediate information about soil conditions. It provides farmers with access to essential soil parameters such as moisture, temperature, pH, electrical conductivity (EC), and macronutrient levels (nitrogen, phosphorus, and potassium), all critical for effective irrigation and soil management. Modbus 7-in-1 sensor Embedded in the soil, continuously monitor these parameters: moisture sensor detects water content, temperature sensor measures soil temperature, EC sensor evaluates acidity or alkalinity, pH sensor assesses salinity levels, and nutrient sensor detects macronutrient levels (nitrogen, phosphorus, and potassium). The data collected is processed by an ESP32 microcontroller, which filters and converts raw readings into accurate numerical values. These

results are displayed on an LCD screen and simultaneously transmitted via email to a cloud platform for storage, analysis, and historical tracking. The cloud system enables data visualization and insight generation, allowing users to monitor soil conditions remotely, receive alerts, and make informed decisions about irrigation and fertilization. Designed with energy efficiency in mind, the system is powered by rechargeable batteries, making it highly suitable for off-grid and remote agricultural areas. Upon powering on, the system displays "Connecting" while it searches for an internet connection. Once connected, the system prompts the user to "Insert," indicating the placement of the soil probe in the ground. The sensor readings are then displayed in real-time on the screen and transmitted to the designated email address, ensuring both immediate and remote access to soil health data. This continuous feedback loop enables smarter resource management, supports improved crop health, and enhances overall agricultural productivity.

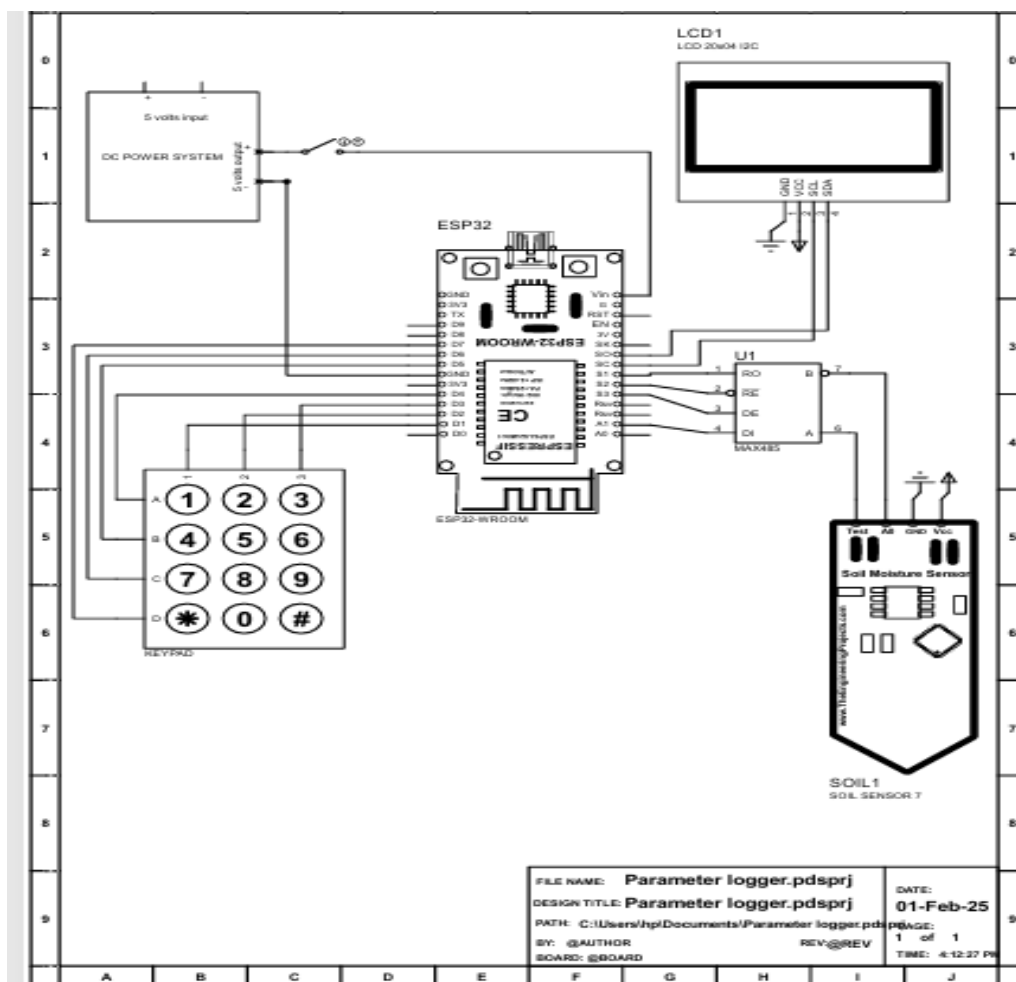


Fig. 3. Circuit diagram of an IoT-enabled in-situ soil monitoring system

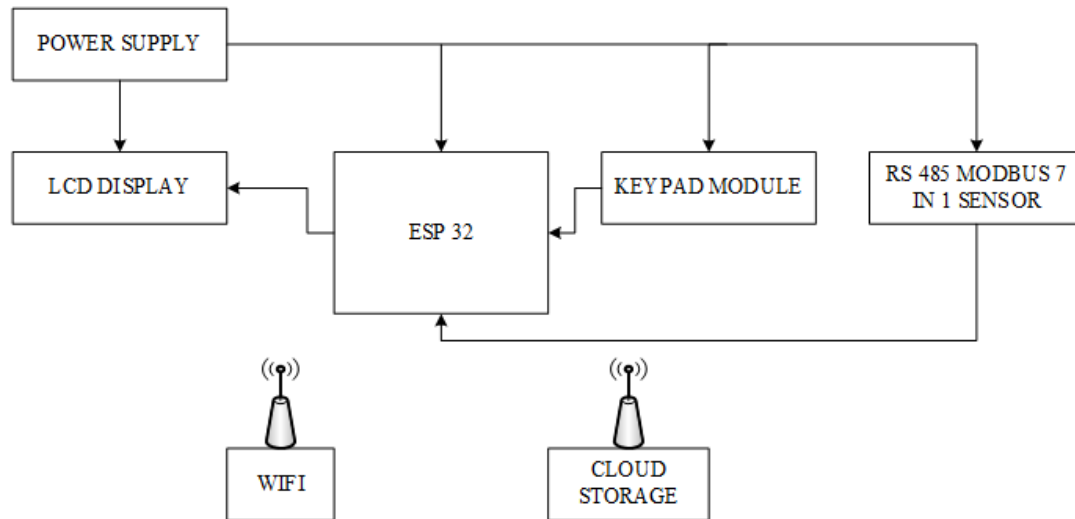


Fig. 4. Block diagram of an IoT-enabled in-situ soil monitoring system

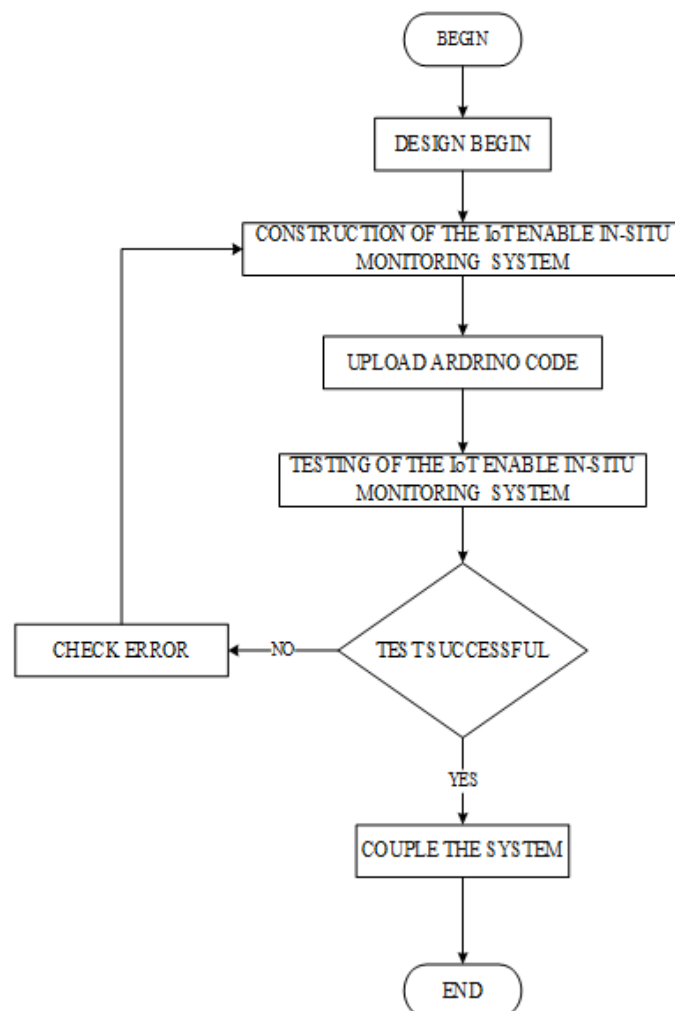


Fig. 5. Construction Flow Chart of an IoT-Enabled In-Situ Soil Monitoring System

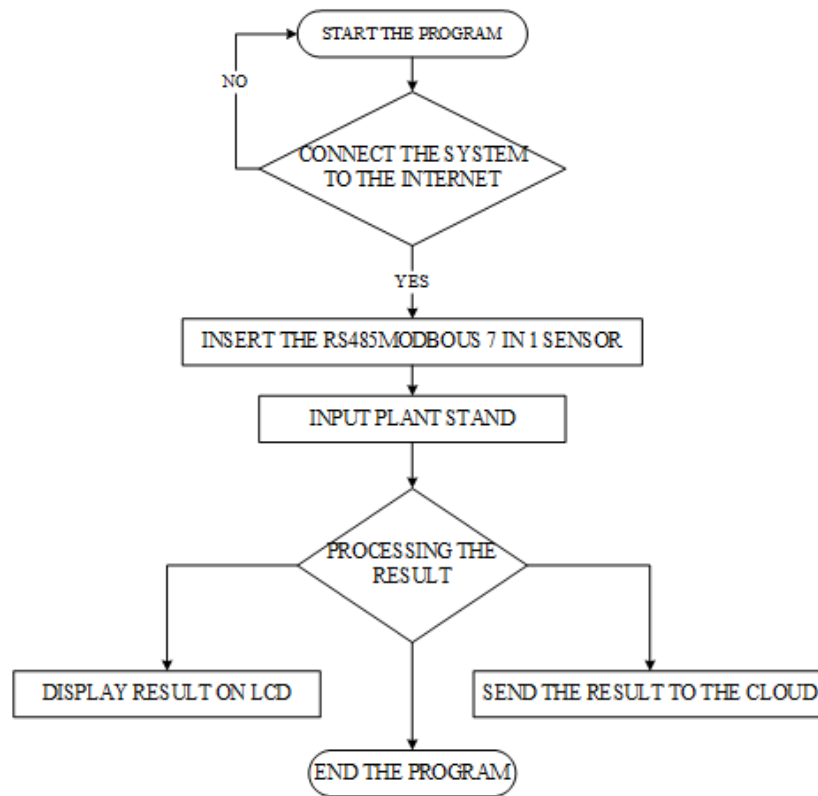


Fig. 6. Working Flow Chart of an IoT-Enabled In-Situ Soil Monitoring System

### 3. RESULTS AND DISCUSSION

The IoT-enabled in-situ soil monitoring system was successfully designed, implemented, and tested, as shown in Fig. 7; the system provides real-time monitoring of essential soil parameters. The system included sensor to check soil moisture, temperature, pH, electrical conductivity (EC), and levels of important nutrients (nitrogen, phosphorus, and potassium), connected to an ESP32 microcontroller, an LCD screen for local readings, and a feature to send data to the cloud for monitoring from afar. Both laboratory and field tests were conducted to evaluate the system's performance, accuracy, and responsiveness under diverse soil and environmental conditions.

#### 3.1 Sensor Performance and Accuracy

The calibration of the developed system was successfully completed prior to deployment to ensure measurement accuracy. A standard solution of 1000 ppm was prepared for nitrogen ( $\text{NH}_4\text{Cl}_2$ ), phosphorus ( $\text{Na}_3\text{PO}_4$ ), and potassium (KCl). Electrical conductivity (EC) and pH measurements were performed using a Hanna Instruments EC and pH meter, while a digital

hygrometer was used to monitor temperature and moisture. The results indicated that the EC and pH values matched the expected ranges for the standard solutions, confirming the accuracy of the calibration standards.

During the calibration process, environmental conditions were carefully controlled using the digital hygrometer. We maintained the temperature between  $26^\circ\text{C}$  and  $28^\circ\text{C}$ , and the relative humidity ranged from 55% to 60%, providing stable conditions necessary for reliable sensor calibration.

The performance of the individual sensors within the RS485 Modbus 7-in-1 sensor module was rigorously evaluated.

**Soil Moisture:** The sensor consistently detected soil water content within an acceptable error margin of less than 3% when compared to standard gravimetric methods.

**Temperature (Ambient and Soil):** The sensor recorded deviations of less than  $0.5^\circ\text{C}$ , closely aligning with the readings from calibrated digital thermometers.



**pH Sensor:** The pH sensor maintained high accuracy throughout the calibration process. A graph was plotted comparing the developed system's pH readings (ranging from 3 to 9) with the Hanna Instruments pH meter readings (ranging from 1 to 14), using a laboratory-grade pH meter as a reference. The comparison demonstrated strong alignment within the overlapping range, confirming the sensor's reliability for practical soil monitoring applications.

**Electrical Conductivity (EC) Sensor:** The EC sensor effectively monitored salinity levels and demonstrated excellent sensitivity to variations in nutrient concentrations.

**Nutrient Detection (NPK):** The sensor module successfully found nitrogen, phosphorus, and potassium, showing values about twice as high as the standard solution we prepared (around 1999 ppm for a 1000 ppm standard). This outcome is consistent with the manufacturer's specifications regarding the sensor's output behavior. Checking the sensor with standard lab methods showed it was accurate after using the right correction factor, proving that the system is

dependable for measuring soil fertility in both lab and field settings.

The IoT-enabled in-situ soil monitoring system produced results that closely matched those from standard lab instruments, indicating that the sensors were correctly installed and capable of delivering accurate, consistent, and reliable measurements in controlled settings.

### 3.2 System Responsiveness and Real-Time Monitoring

The system demonstrated effective real-time monitoring with an average data acquisition and processing time of less than 15 seconds. The ESP32's Wi-Fi module displayed sensor readings on the LCD screen and transmitted them to a designated email. This procedure enabled remote monitoring and data logging for further analysis. Time-series plots of the transmitted data confirmed the system's stability and ability to capture trends in soil parameters throughout different periods of irrigation and environmental changes.



Fig. 7a. Developed soil in-situ system (construction)



Fig. 7b. Readings displayed during calibration



Fig. 7c Developed soil in-situ system during calibration



Fig. 7d. Developed soil in-situ system

### 3.3 Cloud Integration and Data Management

The email-based cloud transmission approach was a simple and effective solution for remote data access. While it lacked real-time dashboard visualization, it allowed data archiving and retrieval for trend analysis. Future versions could integrate advanced IoT platforms such as ThingSpeak or Blynk for interactive visual dashboards and automated alerts.

### 3.4 Power and Energy Efficiency

Powered by rechargeable batteries, the system maintained continuous operation for over 48 hours without the need for recharging, demonstrating its suitability for off-grid and rural agricultural environments. The energy consumption of the ESP32 microcontroller, connected sensors, and other components remained within safe and efficient limits, while the charging system reliably replenished the battery levels, ensuring consistent performance and long-term sustainability.

### 3.5 Implications for Precision Agriculture

The system offers a cost-effective and scalable solution for precision agriculture. By providing continuous and accurate feedback on soil conditions, farmers can make informed decisions about irrigation scheduling, fertilization, and crop health management. The integration of macronutrient (NPK) monitoring in future iterations could further enhance the decision-making process.

## 4. CONCLUSIONS

The creation of a soil monitoring system that uses IoT technology has shown great promise for improving precision agriculture by providing real-time, accurate, and ongoing soil data. By integrating sensors, microcontrollers, and wireless communication technologies, the system effectively monitors key soil parameters, such as moisture, temperature, electrical conductivity, and the percentage of hydrogen, nitrogen, phosphorus, and potassium, enabling informed decision-making for irrigation, fertilization, and overall crop management. The modular and scalable design ensures adaptability across various soil types and agricultural settings, while the cloud-based data logging and visualization platform supports remote access and analysis. Field testing

confirms the system's reliability, responsiveness, and energy efficiency, making it a practical solution for modern agricultural practices. This research provides a foundational step toward smarter, data-driven farming systems, contributing to sustainable resource utilization, increased crop yields, and reduced environmental impact. Future work will focus on integrating advanced analytics and machine learning algorithms to further enhance predictive capabilities and system automation.

## 5. RECOMMENDATIONS

Based on the successful development and calibration of the IoT-enabled in-situ soil monitoring system, the following recommendations are proposed to guide further refinements and real-world applications:

1. **Integration with Smart Irrigation Systems:** To maximize the utility of real-time soil data, the monitoring system should be integrated with automated irrigation systems. The integration will enable closed-loop control for optimized water usage based on current soil conditions.
2. **Data Analytics and Machine Learning:** Incorporating advanced data analytics and machine learning models can enhance decision-making by predicting soil trends, crop performance, and irrigation needs based on historical and real-time data.
3. **User Interface Improvement:** The development of a user-friendly mobile or web-based dashboard will enable farmers and agricultural stakeholders to easily visualize, interpret, and act on the collected soil data.
4. **Pilot Deployment and Stakeholder Training:** Before large-scale adoption, pilot projects should be conducted in diverse agricultural environments, along with training for farmers and extension workers to ensure effective use and maintenance of the system.

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## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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