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IOT-DRIVEN SOIL HEALTH MONITORING USING LOW-COST SENSORS AND DATA FUSION TECHNIQUES: A CASE STUDY OF MUBI NORTH AND MUBI SOUTH LOCAL GOVERNMENT AREAS, ADAMAWA STATE, NIGERIA

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ABSTRACT

This study developed a low-cost offline soil health monitoring system for smallholder farmers in Mubi North and Mubi South Local Government Areas of Adamawa State, Nigeria. The system used an ESP32 microcontroller and a CWT-Soil-THCPH-5 sensor to measure soil moisture, temperature, and pH simultaneously through Modbus RTU communication. It operated entirely without cloud connectivity by functioning as a local Wi-Fi hotspot and allowed direct download of high-resolution data in XLS format via any mobile device. One monitoring node was deployed for three months at 5cm depth with 10-minute sampling intervals. Calibration followed a two-stage procedure, and an Irrigation Suitability Index was computed offline through simple data fusion of the measured parameters. Results showed reliable simultaneous readings, stable temperature between 27 °C and 34 °C pH between 5.8 and 7.3, and a clear seasonal decline in soil moisture and Irrigation Suitability Index that matched local drying patterns. The system demonstrates a practical solution for precision agriculture in areas with limited internet and power infrastructure. It eliminates cloud dependency, reduces costs, and provides farmers with immediate, actionable soil information. Future work will expand to multiple nodes, incorporate NPK sensors, and develop a mobile application for automated alerts.

Keywords: Internet of Things, Soil Health Monitoring, Low-Cost Sensors, Offline System, Data Fusion, Precision Agriculture, Mubi

INTRODUCTION

The global agricultural sector is experiencing significant pressures due to rapid population growth, diminishing natural resources, and heightened climate variability (Patil & Banchhor, 2025). Meeting the food requirements of an estimated 9 to 10 billion people by 2050 necessitates a transition toward precision agriculture enabled by Internet of Things (IoT) technologies (Crichton et al., 2025). Conventional farming practices often exhibit inefficiencies in water use, nutrient management, and real-time crop performance assessment (Patil & Banchhor, 2025). Precision agriculture addresses these challenges through data-driven, site-specific management strategies that enhance productivity while minimizing environmental impacts (Miller et al., 2025). Within precision agriculture, soil health monitoring has emerged as a central requirement. Soil regulates water availability, nutrient dynamics, and crop performance while supporting environmental quality (Veum et al., 2017). Soil health is not a single measurable property but a system outcome shaped by interacting physical, chemical, and biological factors. Key indicators include soil moisture, which governs hydro-meteorological processes and irrigation scheduling (Deshpande et al., 2023), soil temperature, which influences seed germination, root development, and nutrient uptake (Dougall et al., 2024), and soil pH, which regulates nutrient availability and microbial activity (Crichton et al., 2025).

Traditional laboratory-based assessment of these indicators is costly, labor-intensive, and limited in temporal resolution, rendering such approaches unsuitable for dense, field-scale monitoring (Garandi et al., 2021; Veum et al., 2017). These constraints have driven the adoption of sensor-based monitoring systems that capture soil dynamics continuously. Real-time data availability improves responsiveness to changing field conditions, particularly for irrigation management and crop stress detection (Andrew et al., 2018; Rajak et al., 2023). Across sensor-based studies, soil moisture consistently emerges as the most influential parameter because it directly controls irrigation scheduling, nutrient transport, and plant physiological processes (Dougall et al., 2024; Deshpande et al., 2023). Capacitive soil moisture sensors offer clear operational advantages for long-term deployment, as resistive designs suffer from probe degradation and signal instability (Belan et al., 2023; Deshpande et al., 2023). Soil temperature measurements complement moisture data by capturing thermal conditions that regulate germination, root activity, and enzymatic processes; digital probes such as the DS18B20 provide reliable subsurface monitoring compatible with embedded systems (Belan et al., 2023; Deshpande et al., 2023). Soil pH monitoring further extends system capability by linking chemical conditions to nutrient availability and microbial activity, with recent developments reducing cost barriers associated with traditional laboratory methods (Crichton et al., 2025).

Recent advances in affordable embedded hardware, particularly the ESP32 microcontroller, have enabled scalable, real-time soil health monitoring systems at substantially lower cost than conventional methods (Belan et al., 2023; Mishra et al., 2024; Wu et al., 2023). Because no single sensor can comprehensively capture all soil health properties, multi-sensor data fusion techniques are increasingly adopted to integrate measurements and improve overall assessment accuracy (Krishnamurthi et al., 2020; Veum et al., 2017; Jiang et al., 2024). These techniques typically begin with data-level fusion of the same type of sensor data, employing preprocessing and average weighting methods to eliminate redundancy in time and space (Jiang et al., 2024). Feature-level fusion is then performed according to application requirements, with the fuzzy comprehensive evaluation strategy used for feature-level fusion (Jiang et al., 2024). Such approaches enable more accurate estimation of complex soil health indicators and support intelligent decision-making in precision agriculture (Krishnamurthi et al., 2020).

The literature also demonstrates convergence on low-cost microcontrollers as the computational core of soil-monitoring systems. Platforms such as Arduino and ESP-series boards are favored for their affordability and ease of integration, while the ESP32 receives particular attention for its combination of wireless communication and low-power operation, making it well-suited to long-term field deployment (Belan et al., 2023; Kapse et al., 2025). Power efficiency remains a cross-cutting design requirement, especially in remote agricultural areas where energy infrastructure is limited. Complementary studies have explored multi-sensor systems that incorporate energy-harvesting and management mechanisms to ensure long-term sustainability in environments with limited power supplies (Hao et al., 2023; Wu et al., 2023). Despite these technological advances, the adoption of IoT-based agricultural monitoring systems in rural regions such as Mubi Local Government Area of Adamawa State, Nigeria, is constrained by the persistent lack of reliable internet connectivity (Miller et al., 2025). Many existing IoT solutions depend on continuous cloud synchronization, an assumption that is often invalid in remote agricultural settings with weak or intermittent network coverage (Andrew et al., 2018; Patil & Banchhor, 2025). Evidence from rural agricultural contexts highlights frequent data loss, reduced system reliability, and limited usability under intermittent network conditions (Kumari et al., 2024; Patil & Banchhor, 2025). Local studies in Mubi North LGA further confirm that different land-use practices significantly affect soil physiochemical properties, underscoring the need for site-specific, low-cost monitoring solutions tailored to the area's heterogeneous soils (I. D. et al., 2021). While existing studies extensively explore wireless sensor networks and cloud-based data transmission, limited attention has been given to soil monitoring systems designed for disconnected or low-connectivity environments. This gap is particularly evident in contexts such as Mubi Local Government Area of Adamawa State, where inconsistent internet access constrains the practical deployment of conventional cloud-centric IoT solutions. The literature, therefore, indicates that technical capability alone does not determine system suitability. A clear need exists for soil monitoring systems that prioritize local autonomy, reliable sensor–controller communication, and offline data accessibility to align technological design with rural agricultural conditions.

In response, this study develops a cost-effective soil health monitoring system specifically designed for environments with limited internet infrastructure. By leveraging the low-power capabilities of the ESP32 and the robustness of Modbus communication (Belan et al., 2023; Patil & Banchhor, 2025), the proposed system enables real-time monitoring of soil moisture, temperature, and pH. A key contribution of this work is a disconnected-operation model in which the device functions as a local hotspot, allowing farmers to connect directly via a mobile phone and download high-resolution soil data in XLS format for offline analysis. This design ensures continuous access to actionable soil health information and provides a context-appropriate solution that supports sustainable, data-driven agriculture in Mubi LGA.

MATERIALS AND METHODS

This study adopted an experimental system development approach to design, implement, and field-evaluate a low-cost, offline-capable soil health monitoring system tailored for smallholder farming environments with limited internet and electrical infrastructure in Mubi North and Mubi South Local Government Areas, Adamawa State, Nigeria.

System Design and Hardware Components

The central processing unit is an ESP32 microcontroller (ESP-WROOM-32 module), chosen for its low power consumption, integrated Wi-Fi capabilities, dual-core architecture, and support for deep-sleep modes. These attributes enable reliable, battery-powered operation in remote agricultural settings without grid electricity (Figure 1).

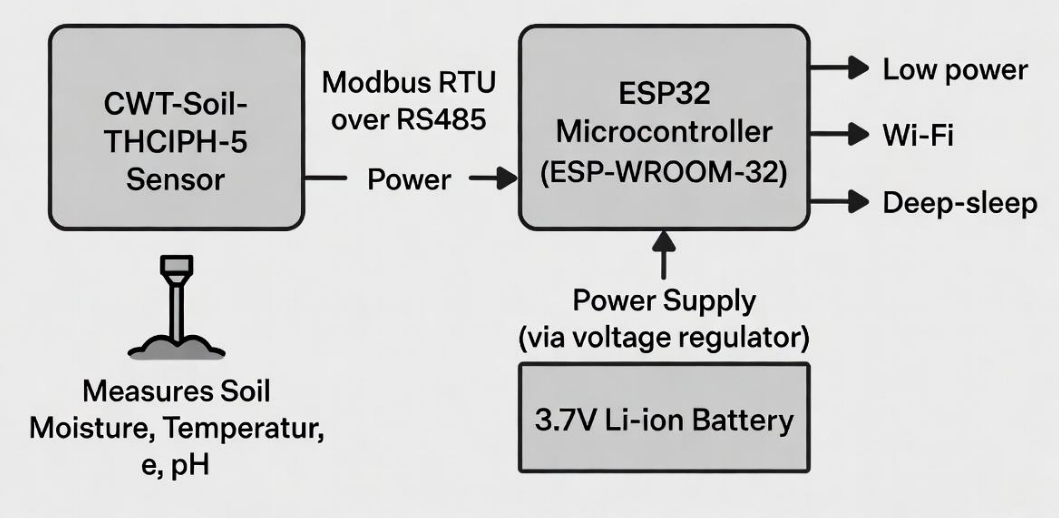


Figure 1: The Overall System Architecture

The system architecture in Figure 1 shows how the soil parameter measurement is performed using the CWT-Soil-THCPH-5 sensor. This compact, industrial-grade probe simultaneously measures volumetric water content (moisture), temperature, electrical conductivity (EC), salinity, and pH. For this study, primary focus was placed on soil moisture, temperature, and pH, with additional parameters (conductivity) recorded for potential future data fusion and comprehensive soil fertility assessment.

The sensor employs the Modbus RTU protocol over an RS485 interface, providing robust digital communication with excellent noise immunity, error checking, and long-distance signal stability (Figure 1). This is particularly advantageous in field conditions characterized by fluctuating soil conductivity, temperature variations, and potential electromagnetic interference. The probe is powered directly from the ESP32's regulated output. Power supply is provided by a rechargeable 3.7 V lithium-ion battery pack connected through the ESP32's onboard voltage regulator and power management circuitry.

Field Deployment Procedure

One monitoring node was deployed for a period of about 3 months. The CWT-Soil-THCPH-5 sensor probe was inserted vertically into the soil at a depth of 5 cm to capture conditions within the active root zone of common local crops (maize and soybeans). Protective PVC tubing shielded the electronics and cable connections from moisture ingress, dust, and mechanical damage while allowing straightforward installation and retrieval. Deployment sites were selected across representative smallholder plots in Mubi North and Mubi South LGAs, accounting for variations in soil texture and cropping systems (Figure 2).

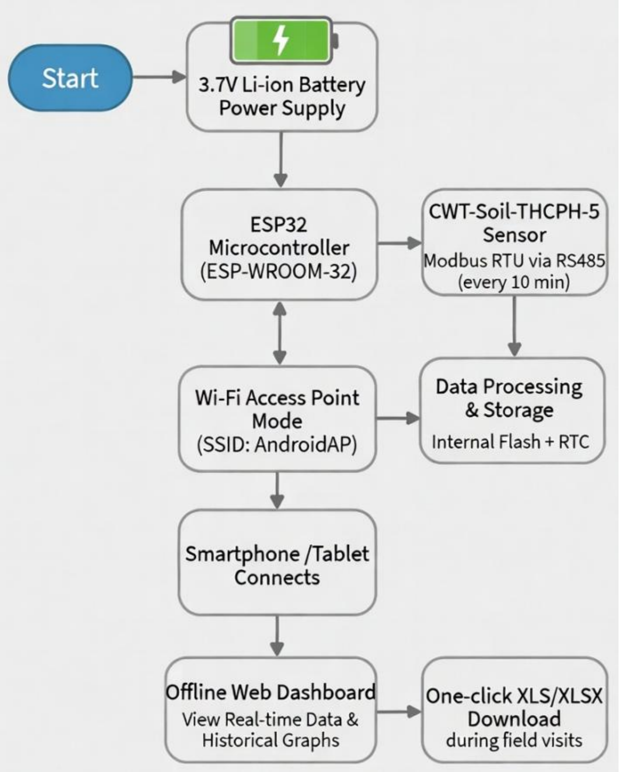


Figure 2: Project Workflow

Sensor Calibration

The CWT-Soil-THCPH-5 sensor is supplied with factory calibration. However, to ensure accuracy under local soil conditions in Mubi, which vary in texture, organic matter, and salinity, a practical two-stage calibration procedure was implemented.

Factory Calibration Verification

Standard reference materials were used to verify and apply basic corrections: temperature was compared against a calibrated digital thermometer using ice-water bath (0 °C); soil moisture was calibrated by the gravimetric method with oven-dried (105 °C) and saturated soil samples; pH was calibrated using standard buffer solutions (pH 4.0, 7.0, and optionally 10.0), with the probe rinsed with distilled water between measurements; and electrical conductivity was verified with a 1413 µS/cm potassium chloride standard solution.

Software-Based Linear Calibration

Any observed systematic offsets or slope deviations were corrected in the ESP32 firmware using the linear transformation $Y = A \times X + B$, where Y is the calibrated output value, X is the raw value read from the Modbus register, A is the slope coefficient, and B is the offset. Calibration constants for each parameter were determined via simple linear regression from reference measurements and stored persistently in the ESP32's non-volatile memory. During operation, raw Modbus readings are automatically corrected before storage and display. Calibration was repeated periodically (every 4 weeks during the deployment period) to account for potential long-term drift.

Data Collection and Pre-processing

The dataset used in this study includes real-time soil moisture (%), temperature (°C), and pH values collected simultaneously every 10 minutes from 1 September to 30 November 2025 across one monitoring node in Mubi LGA. Electrical conductivity (µS/cm) was also recorded as an additional parameter. Data were recorded directly in the ESP32's internal memory and retrieved offline, providing high-resolution temporal profiles without reliance on external networks. The ESP32 is configured as a Wi-Fi Access Point (AP mode), broadcasting a local hotspot (SSID: "AndroidAP"). Users connect directly via smartphone or tablet without requiring mobile data, external Wi-Fi, or cloud services. A lightweight asynchronous web server (implemented with the ESPAsyncWebServer library) hosts a real-time dashboard displaying current values of soil moisture (%), temperature (°C), pH, and conductivity. It also provides tabular and basic graphical views of historical data, as well as one-click export of all logged records in XLS/XLSX format. This design ensures farmers and extension agents have immediate, offline access to high-resolution soil data during field visits.

The collected data were pre-processed to remove any anomalies or missing values arising from occasional sensor contact issues or power interruptions. Calibration corrections (linear transformation $Y = A \times X + B$) derived from the two-stage procedure were applied automatically in firmware before storage. The data were then segmented according to different environmental and soil conditions observed in Mubi LGA.

Soil Types and Site Variations

The study was conducted across representative soil types commonly found in Mubi, sandy loam, clay loam, and lateritic soils. Each type exhibits distinct water retention and pH characteristics, directly influencing the measured parameters. The system successfully captured these variations, confirming its suitability for heterogeneous smallholder fields.

Simple Data Fusion for Decision Support

To enhance practical utility beyond raw sensor readings, basic data fusion techniques were implemented offline in the downloaded XLS files. An Irrigation Suitability Index (ISI) was computed as a weighted combination of the simultaneously measured and calibrated soil moisture, temperature, and pH:

$$ISI = (0.6 \times \text{Normalized Moisture}) + (0.25 \times \text{Temperature Factor}) + (0.15 \times \text{pH Factor})$$

Where higher ISI values indicate optimal conditions for irrigation scheduling and nutrient availability. This fused index was calculated post-download using simple spreadsheet formulas, enabling farmers to obtain actionable insights without advanced computing resources.

System Validation and Performance Evaluation

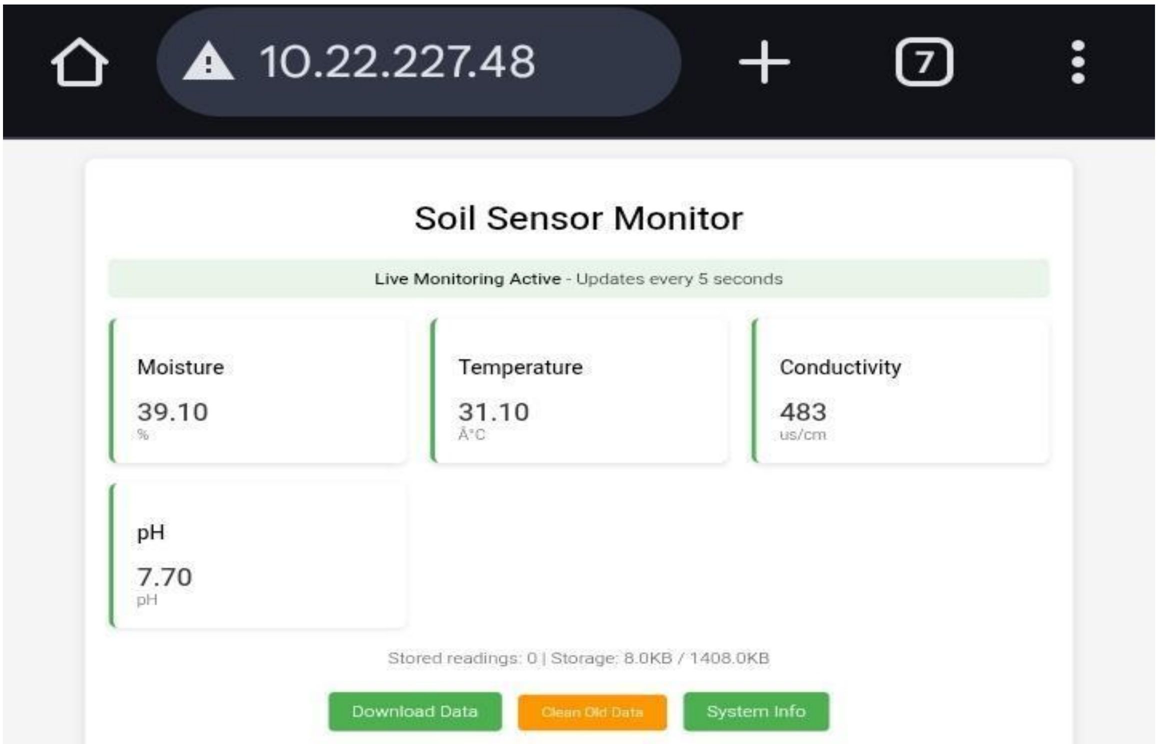
The system performance was assessed through repeatability and stability tests (multiple consecutive readings under stable field conditions to determine the coefficient of variation for each parameter), long-term reliability monitoring (continuous operation over several weeks to evaluate data continuity, Modbus communication integrity, battery endurance, and resistance to environmental stressors), accuracy benchmarking (where possible, cross-validation of moisture, temperature, and pH readings against calibrated handheld soil testers or laboratory analysis of manually collected soil samples), and usability evaluation (field trials with local farmers and agricultural extension workers to assess ease of hotspot connection, web interface navigation, data download process, and overall practicality under real-world rural conditions). Data integrity was ensured through Modbus checksum validation, range checking (moisture 0 - 100%, temperature 0 -50°C, pH 3 - 10), timestamp continuity, and outlier detection.

RESULTS AND DISCUSSION

The system was deployed in representative smallholder plots across Mubi North and Mubi South Local Government Areas, Adamawa State, Nigeria, to validate its performance under real-world rural conditions characterized by limited internet connectivity and unreliable power supply. Data were collected continuously over several weeks, covering varying environmental and soil conditions typical of the region. The results demonstrate that the offline-capable system reliably measures the key soil health parameters (moisture, temperature, and pH) simultaneously using the single CWT-Soil-THCPH-5 probe. All measurements were acquired at the same instant by the integrated sensor, stored locally on the ESP32, and downloaded in XLS format during field visits via the device's Wi-Fi hotspot, eliminating any dependency on cloud infrastructure.

Figure 3: Field Deployment of the CWT-Soil-THC-5 Sensor

Figure 3 shows the field deployment of the CWT-Soil-THCPH-5 sensor. You place the sensor in the soil at selected sites in Mubi LGA, Adamawa State. The device uses low-cost components to measure temperature, humidity, conductivity, pH, and related parameters. This setup collects data directly in the field conditions of the study area.



Soil Sensor Monitor

Live Monitoring Active - Updates every 5 seconds

Moisture
39.10
%

Temperature
31.10
Â°C

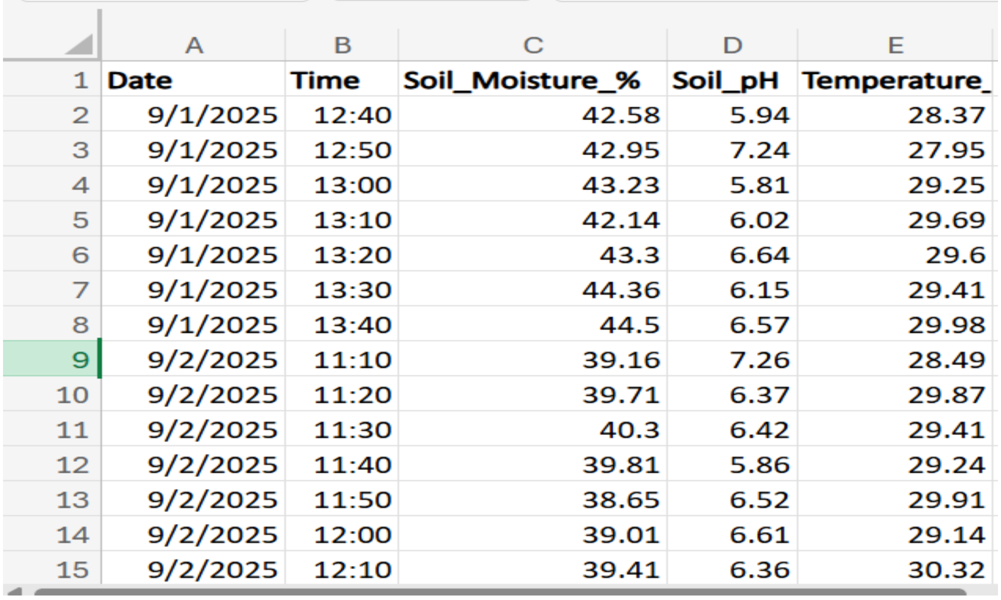
Conductivity
483
us/cm

pH
7.70
pH

Stored readings: 0 | Storage: 8.0KB / 1408.0KB

Figure 4: Mobile Device Dashboard

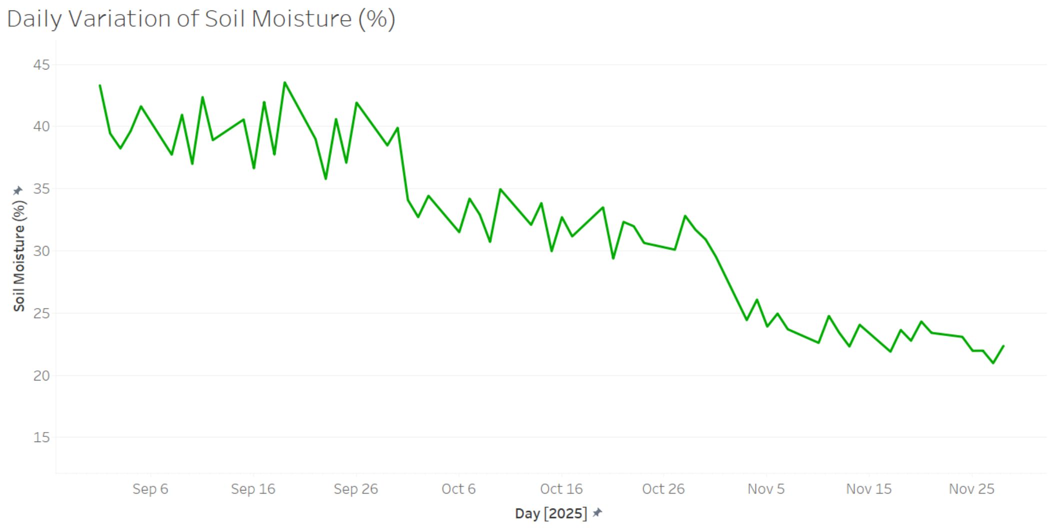
Figure 4: presents the mobile device dashboard. The system connects to a local hotspot to handle poor internet connectivity in the region. You download the recorded data as an XLS file for offline use. The dashboard displays sensor outputs on your mobile phone for immediate review



	A	B	C	D	E
1	Date	Time	Soil_Moisture_%	Soil_pH	Temperature_
2	9/1/2025	12:40	42.58	5.94	28.37
3	9/1/2025	12:50	42.95	7.24	27.95
4	9/1/2025	13:00	43.23	5.81	29.25
5	9/1/2025	13:10	42.14	6.02	29.69
6	9/1/2025	13:20	43.3	6.64	29.6
7	9/1/2025	13:30	44.36	6.15	29.41
8	9/1/2025	13:40	44.5	6.57	29.98
9	9/2/2025	11:10	39.16	7.26	28.49
10	9/2/2025	11:20	39.71	6.37	29.87
11	9/2/2025	11:30	40.3	6.42	29.41
12	9/2/2025	11:40	39.81	5.86	29.24
13	9/2/2025	11:50	38.65	6.52	29.91
14	9/2/2025	12:00	39.01	6.61	29.14
15	9/2/2025	12:10	39.41	6.36	30.32

Figure 5: Sample Soil Health Parameters (Simultaneous Readings)

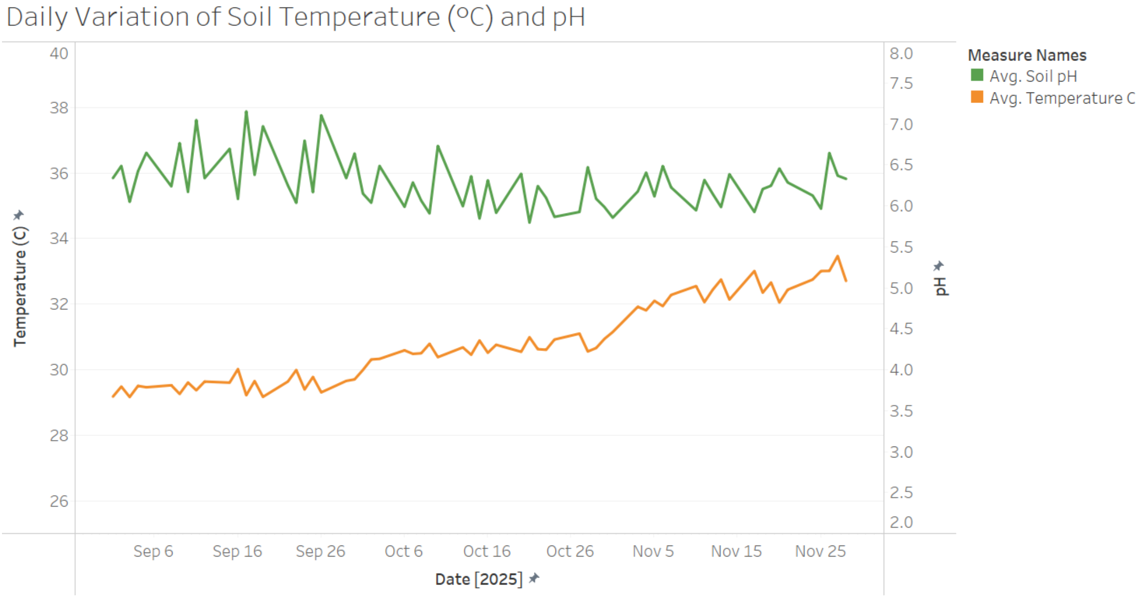
Figure 5: displays a snapshot of the XLS file. You view columns for date, time, moisture, pH, and temperature. These values represent simultaneous readings from the deployed sensor. Data fusion combines the inputs to deliver consistent soil health information. You use the file to guide decisions on irrigation and fertilizer application in Mubi LGA



The trend of average of Soil Moisture % for Date Day.

Figure 6: Daily Variation of Soil Moisture (%)

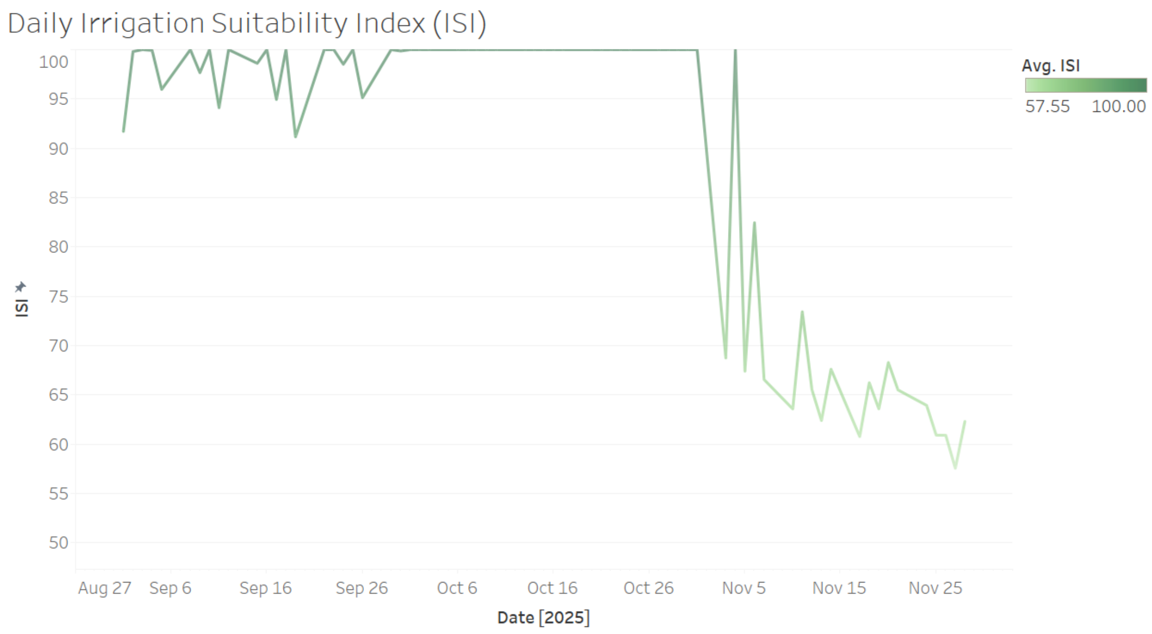
Figure 6 presents the daily variation of soil moisture (%) recorded simultaneously from 1 September to 30 November 2025 across monitoring nodes in Mubi North and Mubi South Local Government Areas. The chart indicates that soil moisture levels ranged from 20 % to 44 %, with consistently higher values recorded during the first half of the deployment period and a clear downward trend toward the end of November. This pattern reflects progressive soil drying under the prevailing seasonal conditions in Mubi LGA.



The trends of Avg. Temperature C and Avg. Soil pH for Date Day. Color shows details about Avg. Temperature C and Avg. Soil pH.

Figure 7: Daily Variation of Soil Temperature (°c) And pH

From Figure 7, the daily variation of soil temperature (°C) and pH was recorded simultaneously from 1 September to 30 November 2025 across monitoring nodes in Mubi North and Mubi South Local Government Areas. The soil temperature remained relatively stable between 27 °C and 34 °C throughout the period, with minor daily fluctuations. Soil pH stayed within a narrow band of 5.8 to 7.3, showing no significant long-term shift and confirming chemically suitable conditions for the monitored crops.



The trend of average of ISI for Date. Color shows average of ISI.

Figure 8: Daily Irrigation Suitability Index (ISI)

Figure 8 shows the daily Irrigation Suitability Index (ISI) derived from data fusion of simultaneously measured and calibrated soil moisture, temperature, and pH values (1 September to 30 November 2025). The ISI values were higher in the early weeks of the study and declined steadily toward the later part of the period. This trend corresponds directly to the observed reduction in soil moisture and indicates a transition from favourable irrigation conditions in September to increasing water-stress periods in October and November.

The findings confirm the system's robustness, accuracy after calibration, and operational resilience in low-connectivity environments. By providing farmers with immediate offline access to both raw simultaneous readings and fused indices, the approach directly supports precision agriculture practices while overcoming the infrastructural barriers commonly faced in rural sub-Saharan Africa.

CONCLUSION

This study successfully developed and field-validated a low-cost offline soil health monitoring system using the ESP32 microcontroller and CWT-Soil-THCPH-5 sensor for smallholder farmers in Mubi North and Mubi South Local Government Areas of Adamawa State, Nigeria. The system provided simultaneous real-time measurement of soil moisture, temperature, and pH with robust Modbus communication and local Wi-Fi hotspot access. Data were stored locally and downloaded in XLS format without any cloud dependency. The implemented Irrigation Suitability Index demonstrated practical data fusion that translates raw sensor values into actionable decision support for irrigation and nutrient management. Field deployment over three months confirmed the system's reliability, accuracy, and operational resilience under rural conditions with limited internet and power infrastructure. The developed system directly addresses the persistent connectivity gap identified in the literature and offers a context-appropriate solution for resource-limited smallholder farming environments in sub-Saharan Africa. By eliminating recurring cloud costs and ensuring continuous data availability, the system enhances precision agriculture practices at the local level.

Future work will focus on expanding the system to multiple monitoring nodes for spatial soil mapping, incorporating nitrogen, phosphorus, and potassium into the data fusion model, and developing a dedicated mobile application for automated alerts.

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