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Performance Evaluation of Resistivity-Based Soil Moisture Sensors for IoT Based Real-Time Monitoring Systems

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ABSTRACT

The Internet of Things (IoT) has emerged as an outstanding innovation in agriculture, enabling precise data collection through digital electronics and wireless communications. The rising consumer demand for organic agriculture and sustainable practices requires continuous monitoring of soil and plant conditions for effective crop management. This project highlights the development and evaluation of an IoT-enabled soil moisture monitoring system aiming to investigate the effectiveness of three commercial resistivity-type soil moisture sensors. The system was implemented using an ESP32 microcontroller and assessed on five soil samples with relative humidity (RH) levels of 0%, 20%, 40%, 60%, and 90%. The sensors' analogue signals were digitized, transmitted via Wi-Fi, and visualized in real-time using the Blynk IoT platform, which is widely accessible on smartphones and desktops. Experimental results demonstrated that sensor performance varied according to stability, sensitivity, and response time. The ABTEST-03 sensor exhibited superior voltage stability with 0.0387 V/%RH sensitivity, attributable to its integrated LM393 comparator module, whereas the ABTEST-01 sensor showed an enhanced sensitivity of 0.0535 V/%RH, likely due to its gold-plated probes that enhance conductivity and resist corrosion. The ABTEST-02 sensor achieved the most satisfactory reaction time, averaging 6 seconds for both rise and fall transitions. Despite minor discrepancies, the findings reveal the strengths and weaknesses of stability, sensitivity, and responsiveness among evaluated sensors. The study emphasizes the importance of precise sensor selection for efficient IoT-based irrigation systems and highlights the detailed characterization of commercial sensors, offering valuable insights for improved smart agriculture efficiency and resource optimization.

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INTRODUCTION

The growth in population is a critical issue in agriculture, projected to escalate by 25% from 7.8 billion in 2020 to nearly 10 billion by 2050. This indicates that agricultural output should increase by almost 70% by 2050 (Hirsch et al., 2019). Substantial volumes of water are necessary to sustain elevated food production levels via irrigated agriculture. Agricultural irrigation contributes to 70% of global water usage, whereas industrial operations and domestic use represent 23% and 7%, respectively (Segaran et al., 2020). The soil's moisture content dictates the ideal water needs of the plants. Therefore, soil moisture sensors can be utilized to improve irrigation management. These sensors have demonstrated the ability to enhance agricultural output and conserve water when utilized as an irrigation scheduling tool. Therefore, it is essential to provide agricultural technology solutions that can mitigate problems and lower production and maintenance costs (Mohamed Zaki et al., 2025).

The development of a variety of soil moisture monitoring techniques that are capable of operating in challenging field settings has been prompted by the necessity for smart irrigation and water-saving strategies in agriculture. At present, soil moisture measurements in the field are conducted using sensing technologies such as dielectric, remote, and thermal sensing, each of which incorporates different technological approaches (Yu et al., 2021). Dielectric impedance-type moisture sensors have become the most typical and have gained popularity due to their affordability, practicality, reliability, and low power consumption. Most resistive sensors have an interdigitated electrode arrangement with moisture-sensitive layers placed between them to touch both electrodes (Mandal et al., 2025). Water adsorption on the electrode surfaces leads to the electrical characteristics of the sensors changing, and the apparent dielectric constant of the soil is indirectly measured to determine soil moisture content. In ionic-type sensing elements, increased moisture increases conductivity and consequently raises the dielectric constant. In 1978, Nakaasa Instrument Co. Ltd. created the 'Hument HPR' moisture sensor, a pioneering thin-film resistive type with a 1% accuracy (Farahani et al., 2014). The moisture sensor produced is a thick and thin film planar moisture sensor with important design characteristics based on an interdigitated structure and a porous membrane.

Continuous soil moisture monitoring is a common practice in digital agriculture aimed at minimizing the impacts of waterlogging and drought, hence enhancing output and profitability. Insufficient moisture levels in the farming area may lead to crop failure and plant mortality, whereas excessive moisture can cause root diseases. Soil monitoring requires measurements that provide time-varying fluctuations in soil qualities and conditions. Assessing the moisture content across the entire field necessitates the farmer to immerse the sensor in several locations, a process that is labor-intensive (Puengsungwan, 2020). The critical aspect of agriculture is the multipoint monitoring of real-time soil moisture data since it directly impacts the management and sustainability of field crops.

The Internet of Things (IoT) was introduced by Kevin Ashton in 1999 to describe internet-connected devices with unique IDs that collect data and interact inside a network (Chamara, 2021; Che Abdullah et al., 2025). In agriculture, IoT technology enables real-time monitoring of critical parameters using sensors connected to the internet via Wi-Fi or other wireless technologies. Technological advancements have made IoT remarkably efficient for real-time data analytics, since devices now automate data collection and transmission. Modern applications often employ low-power microcontrollers such as the ESP32, combined with LoRa/LPWAN or cellular communication for broad connectivity, cloud dashboards for data visualization, and edge pre-processing for localized decision-making (Mansoor et al., 2025; Abdelmoneim et al., 2025; Comegna et al., 2025). This integration enables the ongoing and reliable monitoring of multiple indicators simultaneously. In agriculture, IoT sensors are crucial for collecting comprehensive data across the farming system, which may be employed to identify differences, evaluate predictive models, and enhance sustainability in agricultural practices (Madushanki et al., 2019). Furthermore, cloud-based storage ensures secure data accessible from any location, highlighting the importance of IoT as an efficient and cost-effective system for soil and crop monitoring.

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The deployment of sensors in precision agricultural and environmental applications has significantly increased over the years. The development of soil moisture sensors becomes essential for irrigation systems to enable the implementation of IoT smart farming applications. The apparatus quantifies soil moisture levels, producing a low voltage in dry conditions and a high voltage when moisture is present. Soil moisture sensors are typically employed in moist underground soil, and since most sensors are made of copper, corrosion deteriorates the copper surface of the sensors (Jeong et al., 2018). The corrosion of sensors may lead to the acquisition of erroneous soil moisture data in agricultural IoT monitoring systems, rendering the information unreliable and imprecise for precision agriculture (Puengsungwan, 2020). The moisture sensor utilized must be chosen based on its compatibility with the intended environment, and its efficacy must be assessed accordingly.

Recent research and evaluations demonstrate substantial progress in the stability and drift correction of capacitive sensors (Stroobosscher et al., 2024; Nandi & Shrestha, 2024). The use of deep learning techniques for self-calibration has diminished the need for field recalibration (Wang et al., 2024; Aranda Britez et al., 2025). Capacitive or dielectric sensors, which evaluate soil permittivity, generally provide superior long-term stability and corrosion resistance compared to exposed metal resistive probes. Nonetheless, their efficacy is affected by soil salinity and texture, requiring proper calibration, and they continue to be relatively costly. However, time-domain reflectometry (TDR) and frequency-domain reflectometry (FDR) provide precise and comprehensive soil moisture profiles at various depths, but their expense and complexity restrict their use in cost-effective IoT-based systems (Zhang et al., 2024). Gravimetric analysis remains the laboratory benchmark for soil moisture assessment. Though its destructive and labour-intensive characteristics render it impractical for real-time IoT monitoring (Nandi & Shrestha, 2024). Table 1 provides background for recent developments in precision agriculture by summarizing the most recent research on soil moisture monitoring.

Table 1. Overview of recent studies in precision agriculture addressing soil moisture monitoring.

Technology	Measurement principle	Typical accuracy	Relative cost	Power/ complexity	Pros and cons
Resistive (exposed probes) (Nandi & Shrestha, 2024)	Bulk soil electrical resistance	Low, moderate (± 5–15% VWC)	Very low	Low power, simple	Pros: cheap, easy Cons: corrosion, salinity sensitivity, poor long-term stability.
Capacitive /dielectric (Nandi & Shrestha, 2024)	Permittivity (capacitance)	Moderate–good (± 2–8% VWC)	Low, moderate	Low power, needs calibration	Pros: less corrosion, better stability Cons: texture/salinity effects, needs calibration.
TDR/FDR (reflectometry) (Zhang et al., 2024)	Electromagnetic wave/frequency, permittivity	High (± 1–3% VWC)	High	Higher power, cost	Pros: accurate, depth profiling Cons: expensive, complex for dense node networks.
Gravimetric (laboratory) (Nandi & Shrestha, 2024)	Oven-dry mass measurement	Reference standard (very high)	High (lab time)	Not continuous	Pros: gold standard for calibration Cons: destructive, not real-time.

**Volumetric water content (VWC)*

Previous research has defined the comparative function of resistivity-based sensors and indicated applications where low-cost resistive devices are still suitable for IoT adoption. This work contributes by providing a thorough laboratory characterization of commercial probes and proposing an improved implementation strategy, addressing the limitation of most low-cost sensors, which only detect categorical soil conditions rather than continuous real-time moisture measurement. In this project, a system was

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developed using three different types of soil moisture sensors, an ESP-32 microcontroller, and five soil samples with varying relative humidity (0, 20, 40%, 60%, and 90%). Sensor characterization is essential for the development of an automated coding system for this project. The ESP32 microcontroller was utilized in this system because of its Wi-Fi compatibility, which is important for real-time data transmission. Each soil moisture sensor was linked to the ESP32 microcontroller, which was subsequently interfaced with a smartphone using the Blynk application, utilizing a Wi-Fi shield. Given that not all farmers possess a computer, the Blynk mobile application is recommended for real-time data gathering due to its speed and accuracy, allowing access to soil moisture measurements from any location through the IoT system. This study is to analyze real-time multipoint soil moisture data from each sensor in terms of stability, accuracy, and precision, sensitivity, and response time, evaluate the efficacy of different soil moisture sensors, and integrate the soil moisture monitoring system with IoT applications.

METHODOLOGY

Numerous previous studies utilized comparable combinations incorporating ESP32 microcontrollers and Wi-Fi-enabled Blynk platforms for the real-time monitoring and visualization of soil moisture (Smail et al., 2025; Morchid et al., 2024; Abbas et al., 2025). These studies exhibit analogous techniques that incorporate economical resistivity-based soil moisture sensors with cloud-connected IoT dashboards. The investigation process initiated with the circuit design, wherein the hardware components, including various moisture sensors and the ESP32 microcontroller, were interconnected to create a full circuit. The software implementation was achieved by coding in the Arduino IDE, which served as a compiler, converting the written source code into executable code. Any errors identified during the compilation phase necessitated modifications to the code before testing each sensor with soil samples of varying relative humidity levels. Subsequently, the soil moisture monitoring system was constructed to link with the Blynk IoT platform, enabling real-time monitoring of the user interface on smartphones and desktops. The output voltage of the sensors was examined in relation to relative humidity levels, and the stability, sensitivity, and response time of the sensors were assessed in real-time. The extensive testing and evaluation process was conducted with the three sensors to ensure that the system for monitoring soil moisture was functional and capable of detecting multipoint soil moisture as a result of this research.

Hardware components

The ESP32 DevKit v1 by Espressif Systems is a robust, economical, and energy-efficient microcontroller including integrated Wi-Fi and a dual-mode Bluetooth system-on-chip (SoC). The ESP32 is constructed around a Tensilica Xtensa LX6 32-bit CPU, commonly utilized in IoT applications. It incorporates a dual-core microprocessor (two processors) functioning at 240 MHz, along with integrated antenna switches, RF balun, power amplifier, low-noise receive amplifier, filters, and power management modules (Rathod et al., 2020). The ESP32 board comprises 30 pins that provide connections to external sensors and components for many applications. Among the 30 pins, 24 are GPIO pins designated for interfacing with various sensors to acquire data and relay output to appropriate devices (Keerthana et al., 2021). The microcontroller continuously verified the recorded data against the input data from many sensors.

The board was powered by an onboard micro-USB port that was wired into a power source. This connection was also used to connect the board to a computer and upload programming code via the Arduino IDE. The board includes two power pins: a 5 V pin and a 3.3 V pin. The 5 V pin was used to distribute power directly to the ESP32 and soil moisture sensors system via the controlled power bank 5 V voltage supply.

This research involves three different commercial resistivity-based soil moisture sensors, ABTEST-01, ABTEST-02, and ABTEST-03 shown in Fig 1. It is an economical sensor employed to quantify soil

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moisture level. The sensor is equipped with two prominent exposed pads that serve as probes for insertion into the soil. As current flows through the soil, the sensor detects variations in current between the two conductive probes to ascertain the resistance value, subsequently converting that resistance value into moisture content. The effective conductivity of soil enhances with an increase in soil moisture (Rajkumar et al., 2020). The electronic module detects this voltage drop fluctuation and subsequently outputs a response based on the resistance variation. The observed soil resistivity is influenced by ion concentration; therefore, thorough calibration and regular recalibrations (due to varying organic and salt concentrations) are advised for practical use. The sensor generates an analogue voltage that is proportional to the soil's water content. As the volume of irrigated water increased, the soil exhibited enhanced electrical conductivity due to reduced resistance, but dry soil showed decreased conductivity owing to increased resistance.

Additionally, all three sensors can be powered by a voltage source ranging from 3.3 volts to 5.0 volts and are compatible with numerous microcontrollers. Most commercial resistive moisture sensors have an average lifespan of approximately one year. Fig 1(a) illustrates that the ABTEST-01 sensor's surface has been metallized to improve lifetime, with the probe material being gold-plated to enhance conductivity and corrosion resistance, hence increasing durability. Meanwhile, the probes of the ABTEST-02 sensor are coated with zinc, as in Fig 1(b), while the probes of the ABTEST-03 sensor are coated with nickel. Fig 1(c) depicts the ABTEST-03 soil moisture sensor, which consists of two elements: the sensor module with an LM393 comparator (left) and the probes fitted with two pads for moisture detection (right). The sensor includes both analogue (A0) and digital (D0) outputs via its voltage comparison module, along with a power LED, a digital output LED, and an integrated potentiometer for calibrating the sensitivity of the digital output. The threshold value is evaluated by the LM393 comparator, and upon reaching either the higher or lower threshold, the output LED is triggered. The insertion of probes into the soil is indicated by red and green LEDs, denoting high or low output, respectively.

Experimental setup

This study employed a data gathering system comprising the ESP-32 Devkit V1 microcontroller board and three soil moisture sensors, all coupled to a micro-USB power bank. The power bank was utilized to power the 5 V pin of the microcontroller and provide voltage to the complete system. Furthermore, five mixtures of soil samples were prepared by combining organic-rich soil with water in proportions corresponding to the intended relative humidity content. A digital hygrometer moisture sensor served as the reference instrument to assess and prepare the soil samples with relative humidity levels of 0%, 20%, 40%, 60%, and 90%. The assembly program code for the system was developed using Arduino IDE, employing commands to regulate the microcontroller's Wi-Fi module for data transmission to the IoT platform. The deployed platform was Blynk IoT, utilized to develop a graphical interface for the soil moisture monitoring system on both computer and smartphone, facilitating data collection and analysis visualization. The test setup and materials utilized for this research are presented in Fig 2.

This proposed soil moisture monitoring system is a straightforward model developed utilizing IoT technologies. It comprises a cloud page functioning as a user interface and an IoT device facilitating real-time information changes within the system. The ESP32 was chosen as the microcontroller due to its Wi- fi compatibility, essential for real-time data transmission. Fig 3 illustrates the interface circuit of multipoint moisture sensors, along with the separately evaluated component and module utilizing the ESP32 microcontroller, designed with Fritzing software. The DC power source was directly attached to the microcontroller's 5 V pin, utilizing a 10,000 mAh battery bank. The uploaded computer code enables the circuit to function autonomously whenever it is powered on. The data on soil moisture conditions were collected and transmitted directly to the microcontroller using the moisture sensor. The performance of all moisture sensors was evaluated using soil samples with five varying levels of relative humidity.

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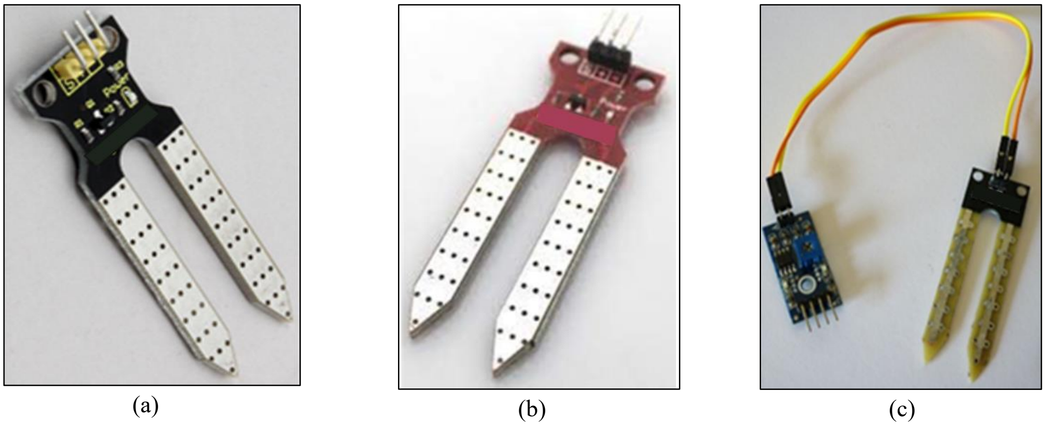

Fig. 1. Soil moisture sensors (a) ABTEST-01, (b) ABTEST-02, and (c) ABTEST-03.

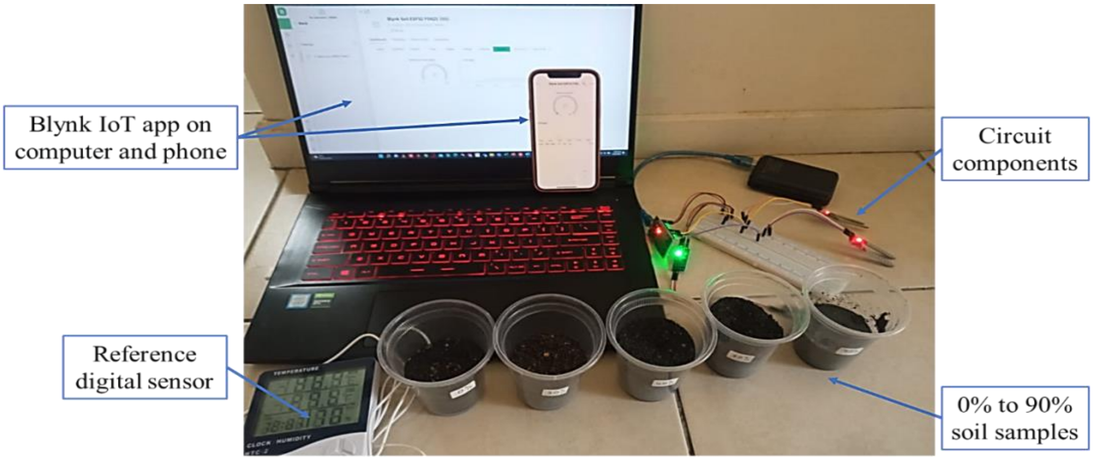

Fig. 2. Apparatus and materials of the system.

The soil preparation procedure in this research was standardized according to the previous research to provide uniformity across all experiments (Nagahage et al., 2019). The soil sample was prepared using an organic-rich gardening soil mixture. Soil was oven-dried at 105 °C (± 5 °C) overnight, resulting in 0% relative humidity. Following that, it was divided into five cups of soil samples, and distilled water was gradually added to bring each soil sample up to the predetermined water content. All the soil samples were then mixed carefully to ensure consistent dispersion. The digital hygrometer moisture sensor served as a reference sensor for preparing and measuring the appropriate soil samples at relative humidity levels of 20%, 40%, 60%, and 90%. As shown in Fig 4, the moisture contents of the soil mixture were evaluated by inserting the probe of the digital hygrometer sensor vertically into each soil sample at a uniform depth of roughly 5 cm to verify each sample based on the predetermined relative humidity percentage. The chosen insertion depth was determined to guarantee adequate contact between the sensor probes and the soil matrix, while also aligning with standard root-zone monitoring methodologies in agriculture (Li et al., 2023). Each probe was meticulously positioned at the center of the sample to prevent edge effects or air gaps that could compromise conductivity measurements. The probes were maintained in a steady position during the testing period to reduce movement or displacement, therefore guaranteeing dependable and consistent resistivity-based sensor outputs. To prevent unequal distribution, water was incrementally introduced with continuous agitation, and each sample was covered with plastic wrap to reduce evaporation (Nagahage et al., 2019).

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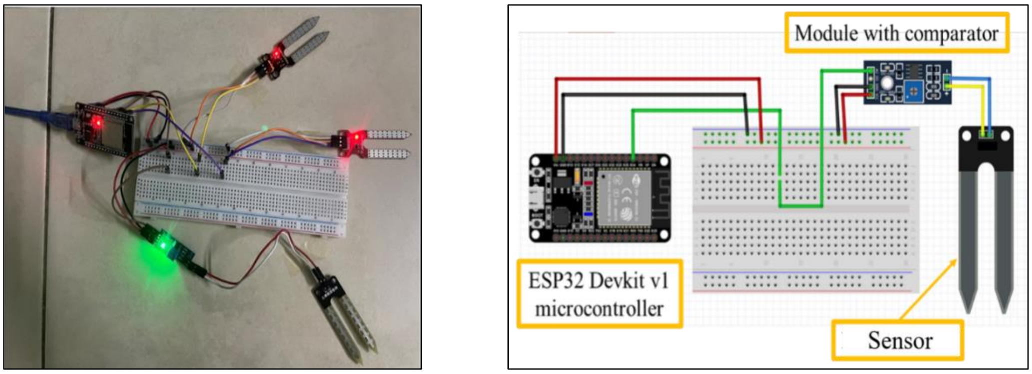
Subsequently, each sensor type was submerged in soil samples with 0%, 20%, 40%, 60%, and 90% RH. The voltage outputs were measured over a duration of about 4 minutes for each sample cycle to generate a graph depicting the response and sensitivity of each sensor type at ambient temperature. Each experiment was repeated three times for each sensor, as illustrated in Fig 5. The moisture sensors were connected to the ESP32 microcontroller and its built-in Wi-Fi module, allowing the system to communicate with the network. Each type of soil moisture sensor was inserted into five soil samples, resulting in analogue voltage outputs. These output data were then gathered and sent to the ESP32 microcontroller, which translated the analogue values into 12-bit digital values corresponding to the soil moisture levels. The data collected by the ESP32 from the soil moisture sensors was transmitted and updated in the Blynk cloud database platform using the established Wi-Fi network. As a result, the experimental setup was completed using Excel to provide a comparative examination of the properties of the three different types of resistive moisture sensors.



(a) (b)

Fig. 3. (a) The interface circuit of multipoint moisture sensors and (b) circuit design using Fritzing software.

(a) (b)

Fig. 4. Soil samples preparation (a) the prepared soil samples were tested with a digital hygrometer sensor to measure the %RH level and (b) soil samples were prepared at 0%, 20%, 40%, 60% and 90% RH conditions.

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Fig. 5. Moisture sensors were inserted into each soil sample for evaluation of sensor and system performance.

RESULTS AND DISCUSSION

IoT software implementation

The Blynk IoT platform was utilized to monitor soil moisture sensor data via IoT. Blynk is an open-source IoT platform that allows you to control hardware remotely, display and save sensor data, and view the device management analytics dashboard. The application, server, and libraries are three vital parts of Blynk. The application itself can construct and develop the user interface. Meanwhile, the server handles all communication between apps and designs, whereas libraries let the system interface with the server via command instructions. The microcontroller's on-chip Wi-Fi enabled the continuous upload of data values collected from soil moisture sensors to the Blynk cloud. The Blynk IoT platform's iOS and Android applications enable wireless control of electronic equipment. It has offered a useful dashboard through which users may develop precise interfaces with various devices. The Blynk application allows managing all components via the Blynk server. The state of hardware virtual pins can be changed using commands accessible from the Blynk app via various types of widgets. This enables users to access the soil condition monitoring system remotely, even without the presence of a computer (Sheth & Rupani, 2018).

The ESP32 microcontroller requires a data connection for the Blynk application to access the Blynk server and retrieve soil monitoring system data from the sensors, enabling real-time monitoring of relative humidity gauges and the voltage SuperChart (Garcia et al., 2018). The codes were designed to enable the gauge and SuperChart to accept data from the moisture sensors for monitoring relative soil humidity and output voltage over time. The communication between the application and the ESP32 was integrated into the code. Upon loading the code into the hardware, the soil moisture status was shown on the Blynk smartphone application and web dashboard when connected to the Wi-Fi network (Abhiram et al., 2020). The test results indicated that the system functioned as designed, with the output voltage represented by a green line on the real-time output voltage SuperChart when soil moisture content was sufficient, and a red line when it was critically low. Fig 6 shows the layout design of the Blynk interface, displaying various relative humidity levels on the smartphone application and web dashboard, including the timeline for real-time voltage output data from the soil moisture sensors.

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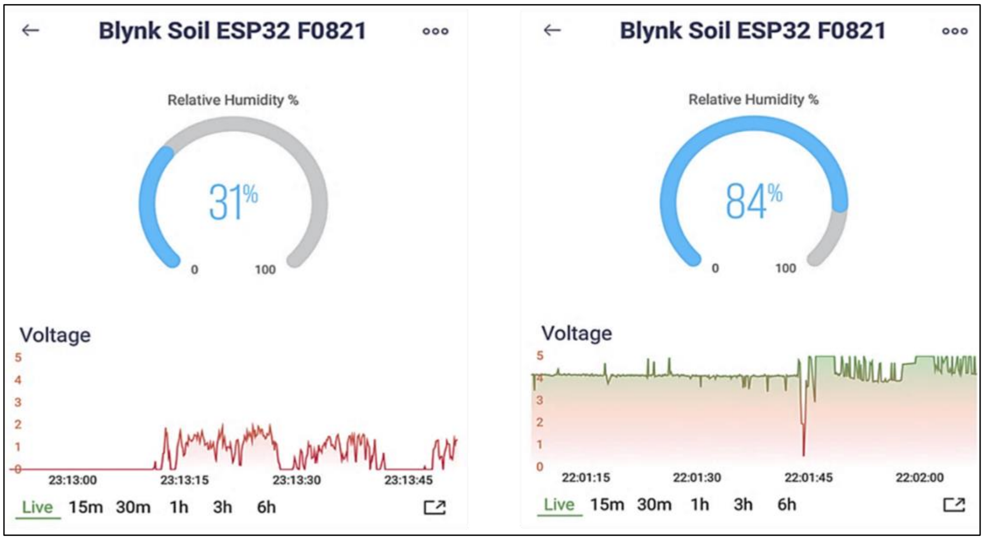

(a)

(b)

Fig. 6. Blynk interface (a) on smartphone application and (b) on web dashboard.

Voltage stability

Soil moisture sensors responded to the water content present in the soil. This research tested three varieties of resistive soil moisture sensors in five soil samples with varying relative humidity (RH) levels. The soil moisture sensors utilized were ABTEST-01, ABTEST-02 and ABTEST-03. The performance of these sensors would be affected by the soil's relative humidity content. The results of this research involved collecting real-time moisture data from each sensor type and then analyzing them by generating graphs showing stability, sensitivity, and response behaviour. The moisture sensor identified water presence by measuring the voltage output, which correlates with Ohm's Law as expressed in Equation 1. It demonstrates the relationship between voltage, current, and resistance, wherein resistance reduces as the sensor is subjected to increased moisture content, leading to elevated voltage (Ngadiman et al., 2022). The sensor consists of two probes that facilitate the passage of current through the soil, which is subsequently examined to ascertain the relative humidity (RH) (Kargas & Soulis, 2012). The ESP32 microcontroller features a 12-bit Analog-to-Digital Converter (ADC) that segments the 0 V to 5 V range into 4096 discrete intervals, where interval 0 corresponds to 0 V and interval 4096 corresponds to 5 V. The ADC microprocessor can

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convert analogue signals into digital values. The equation for calculating the output voltage of the ADC signal is presented in Equation 2.

$$V = IR \tag{1}$$

$$Voltage\ Reading = ADC\ Reading \times \frac{5.0\ V}{4095} \tag{2}$$

Fig 7 shows a graph of output voltage versus time for soil samples ranging from 0% to 90% relative humidity, utilizing three distinct types of sensors: ABTEST-01, ABTEST-02, and ABTEST-03. The soil moisture conditions, assessed using several relative humidity levels, were visually presented for the sensor's sensitivity analyzes. All three sensor readings indicated a voltage of 0 V at 0% relative humidity. Changes were identified in voltage readings at 20%, 40%, 60%, and 90% relative humidity. The three sensor measurements were collected over several minutes to verify the sensor's accuracy. The graph indicates that each moisture sensor type was monitored for three to five minutes to evaluate its stability regarding the accuracy and precision of output throughout each tested soil sample. The ABTEST-03 sensor graph has the highest voltage stability, followed by the ABTEST-02 sensor and the ABTEST-01 sensor, which has the lowest voltage stability attained. This stabilisation is owing to the ABTEST-03 sensor's LM393 comparator module, which eliminated and reduced noise interference via the interface circuit. The comparator contained an operational amplifier, which helped filter the output signal to achieve voltage stability (Reverter, 2018; Nabavi & Nihtianov, 2014). Meanwhile, the absence of an interface circuit comparator for signal conditioning may have contributed to the unstable and inconsistent output data acquired by the ABTEST-01 and ABTEST-02 sensors, reducing their accuracy and precision of stability behaviour. As a result, uncontrollable circumstances occurred, interfering with the output signal due to noise vibration and ambient temperature fluctuations (Nabavi & Nihtianov, 2014; Datta, 2018).

Sensitivity performance

In the graph illustrated in Fig 7, it is obtained to compare the sensitivity performance of every sensor at different levels of relative humidity. The average voltage output values were determined from the response of each sensor obtained in real-time (Fig 6). The voltage response of the three soil moisture sensors (ABTEST-01, ABTEST-02, and ABTEST-03) exhibited a consistent increase with elevated soil moisture levels, indicating their capacity to distinguish between differing situations. The incorporation of error bars offers critical insights into measurement consistency and reproducibility. ABTEST-02 demonstrated consistent performance with moderate error bar ranges throughout all moisture levels, reflecting a balance between sensitivity and dependability. The ABTEST-01 had a broad dynamic range but generated larger error bars, especially at intermediate moisture levels (40% - 60%), indicating increased unpredictability and sensitivity to noise. Meanwhile, ABTEST-03 exhibited the least error bars, signifying reliable outputs, and nevertheless, it has a restricted voltage range, indicating diminished sensitivity to variations in moisture. The results indicate that although all three sensors can monitor soil moisture fluctuations, their reliability differs, as ABTEST-02 provides balanced performance, ABTEST-01 is more sensitive, however less stable, and ABTEST-03 is stable but less responsive.

Due to the modest fluctuations in the output readings of each sensor, particularly the ABTEST-01 and ABTEST-02 sensors, the average values for all three sensor types were utilized for establishing the sensitivity graph of voltage vs RH% values (Adla et al., 2020). From the sensitivity graphs in Fig 8, it can be seen that the voltage output increased linearly in trend when all three sensors were immersed with the increasing relative humidity levels (from 0% RH until 90% RH). The values of average output voltage from 0% to 90% relative humidity of soil samples for each sensor are depicted in Table 2. The average voltage values were gathered to calculate the sensitivity behaviour of every moisture sensor in order to determine the best-performing sensor among the three sensors deployed in the system.

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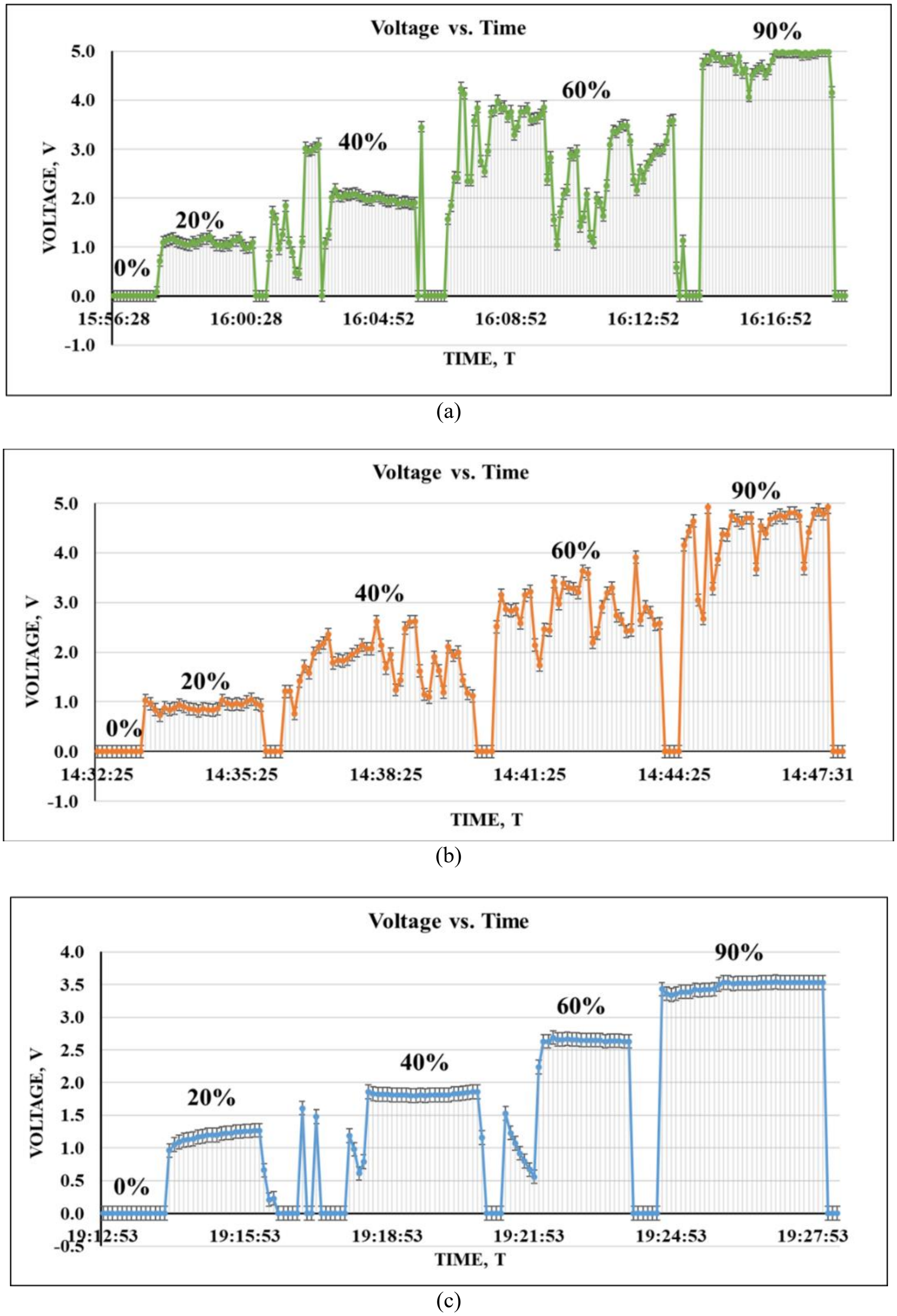

Fig. 7. The voltage response presented with error bars: (a) ABTEST-01, (b) ABTEST-02, and (c) ABTEST-03 tested in soil samples at 0%, 20%, 40%, 60%, and 90% RH. The error bars depict measurement variability, demonstrating variances in sensor stability, with ABTEST-03 producing more consistent outputs, ABTEST-02 maintaining moderate stability, and ABTEST-01 exhibiting higher fluctuations at intermediate moisture levels.

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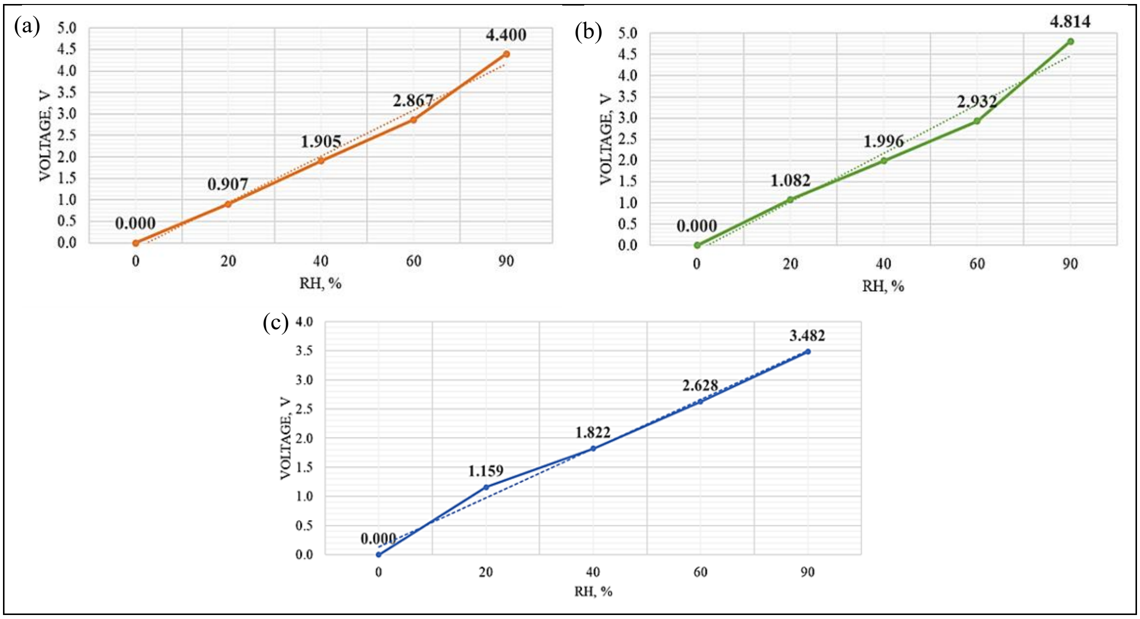

Fig. 8. Response of the sensor (a) ABTEST-02 (b) ABTEST-01 and (c) ABTEST-03.

Table 2. Average output voltage for every sensor

Relative humidity, %	ABTEST-01 Average voltage, V	ABTEST-02 Average voltage, V	ABTEST-03 Average voltage, V
0	0.000	0.000	0.000
20	1.082	0.907	1.159
40	1.996	1.905	1.822
60	2.932	2.867	2.628
90	4.814	4.400	3.482

This investigation employed a sensitivity equation that referenced the difference between the maximum and minimum average voltage values associated with varying relative humidity levels, as indicated in Equation 3 (Kim et al., 2019).

$$Sensitivity = \frac{V_i - V_o}{\%RH_{max} - \%RH_{min}} \quad (3)$$

The sensitivity values for each sensor type were compiled in Table 3 as follows. The data indicates that the ABTEST-01 sensor has the highest sensitivity at 0.0535 V/%RH, surpassing the ABTEST-02 sensor, which has a sensitivity of 0.0489 V/%RH, and the ABTEST-03 sensor, which possesses the lowest sensitivity at 0.0387 V/%RH. The sensor with the highest sensitivity value signifies superior performance; thus, it can be concluded that the ABTEST-01 is the most effective sensor, while the ABTEST-03 is the least effective sensor. The sensitivity behaviour of each sensor was found to be affected by the substances deposited on the electrode surfaces. The ABTEST-01 sensor has superior sensitivity to water molecules owing to its gold-plated composition, in contrast to the potentially corrosive metal-plated materials, such as nickel in the ABTEST-03 sensor and zinc in the ABTEST-02 sensor. The ABTEST-01 sensor has gold-plated probes, recognized for their superior conductivity and resistance to corrosion (Chen et al., 2022;

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Kalita et al., 2016; Yin et al., 2021; Zhou et al., 2019). Moreover, it enhances proton conduction within the hydrogen-bonded networks of water molecules more effectively in gold, rendering the material's dielectric constant highly responsive to moisture in comparison to nickel and zinc. The condensation of adsorbed water on the gold-plated surface facilitates conduction, leading to robust hydrogen bonding that promotes the subsequent adsorption of water molecules diffusing across the sensor film (Farahani et al., 2014; Chen et al., 2022; Liu et al., 2019).

Table 3. Sensitivity value of each sensor

Sensor type	Sensitivity, V/%RH
ABTEST-01	0.0535
ABTEST-02	0.0489
ABTEST-03	0.0387

Response time

Response time represents the interval necessary for a signal to shift between two specified positions at the rising and falling margins of a curve. This research evaluated the time response of the sensor, with the experimental results for each moisture sensor at 20% RH presented in Fig 9. The sensor's response time was typically assessed between the 10% and 90% thresholds on the rising edge of the curve (rise time) and between the 90% and 10% thresholds on the falling edge (fall time). A measurement that lies between the 10% and 90% thresholds may be easier to execute, produce more precise results, and be more pertinent to the application. In scenarios where the signal is not required to stabilize at specific minimum and maximum amplitudes, the overall transition time is probably of less significance.

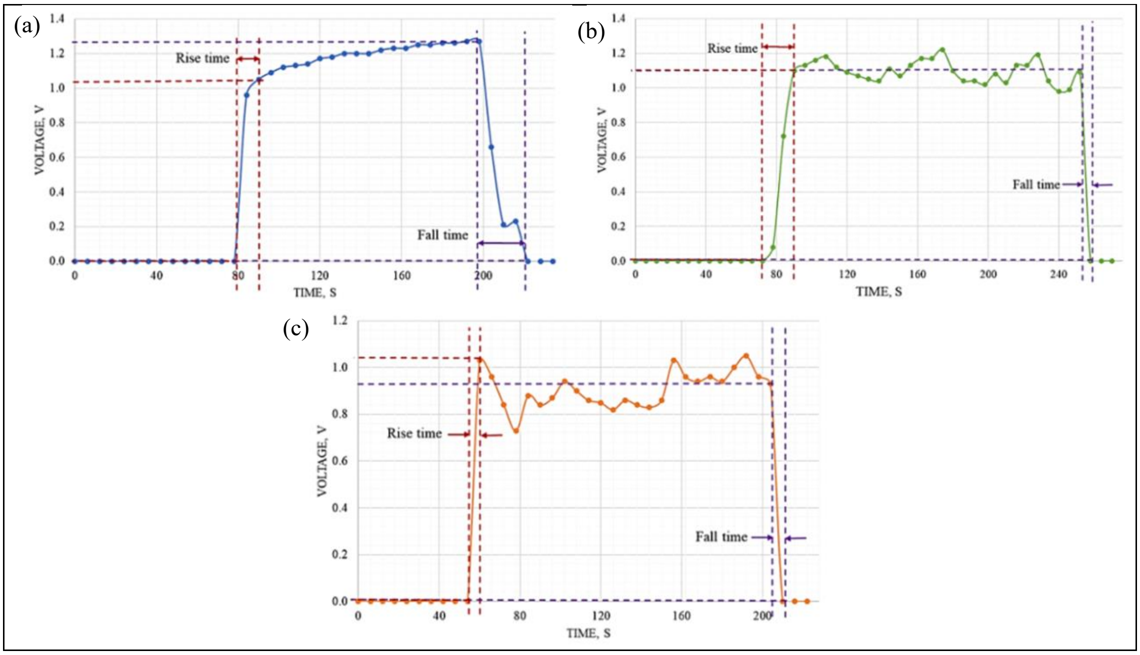

Fig. 9. Comparisons of response time for sensor (a) ABTEST-03 (b) ABTEST-01 and (c) ABTEST-02.

The equations for measuring the reaction time of the three sensors are shown in Equation 4 and Equation 5, where the rise time and fall time for each relative humidity condition were determined correspondingly (Wan Ahmad Aziz et al., 2024).

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$$Rise\ time, \tau_r = \tau_{r1} - \tau_{r2} \quad (4)$$

$$Fall\ time, \tau_f = \tau_{f1} - \tau_{f2} \quad (5)$$

The average response time data for each sensor was gathered from 0% to 90% relative humidity levels using rise time and fall time equations, as shown in Table 4. The response time data indicates that all three sensors recorded a response time of 0 seconds from the initial state of 0% relative humidity level. Nonetheless, there were variations in the response time of each sensor output while measuring the ascending curves from the 0% initial state to the 20%, 40%, 60%, and 90% RH levels, as well as the descending curves from each RH level back to the initial state. Although there are minor variations in the rise and fall times of the three sensor types, the ABTEST-02 moisture sensor clearly has the shortest response time relative to the ABTEST-01 and ABTEST-03 sensors. The ABTEST-03 sensor has the longest rise and fall times at both 20% RH and 60% RH, followed by the ABTEST-01 sensor, and then the ABTEST-02 sensor shows the fastest response times (rise time and fall time).

Table 4. Average response time of each sensor

Relative humidity, %	ABTEST-01		ABTEST-02		ABTEST-03	
	Rise time, s	Fall time, s	Rise time, s	Fall time, s	Rise time, s	Fall time, s
0	0	0	0	0	0	0
20	18	6	6	6	12	24
40	18	18	30	24	30	12
60	30	24	12	6	54	6
90	6	12	6	12	6	6

Moreover, Fig 10 presents a detailed illustration of the response times of the ABTEST-03 moisture sensor throughout relative humidity levels ranging from 0% to 90% relative humidity. The measured rise and fall times indicated that the response time is longest at relative humidity levels of 40% and 90%. The reaction time of the sensors was affected by several contributing factors, including the thickness of the probe coating, which influenced the diffusion rate of water molecules, as well as the size and distribution of the micro-holes on the coating surface, among others (Chen et al., 2022; Liu et al., 2019; Ahmadipour et al., 2016).

System implementation and challenges

The developed system demonstrates the potential for cost-effective, real-time soil monitoring in precision agriculture, offering farmers improved irrigation scheduling, water efficiency, and crop management through connected IoT automation. The proposed resistivity-based soil moisture monitoring system can be expanded for larger field applications or multi-node networks by utilizing the modularity of the ESP32 microcontroller and the adaptability of IoT cloud platforms such as Blynk. To capture geographical soil heterogeneity across extensive agricultural areas, many ESP32 nodes can be strategically distributed, each outfitted with specialized sensor types (e.g., ABTest-01 for sensitivity or ABTest-03 for stability). These nodes may be placed in either mesh or star network topologies, with data from each node wirelessly transmitted to a central gateway and subsequently synchronized to the cloud. This enables the streamlined collection, visualization, and analysis of multi-point soil moisture data on a unified dashboard accessible via smartphones or web platforms.

Moreover, the system's efficacy can be improved by integrating data calibration procedures and automatic correction algorithms to address environmental variations across different soil types and climatic conditions, hence ensuring constant long-term functionality (Aranda Britez et al., 2025). The integration of cloud storage and big-data analytics positions the system as a precision irrigation decision-support tool,

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enabling farmers to implement zone-specific watering plans that optimize water use efficiency and enhance crop yield.

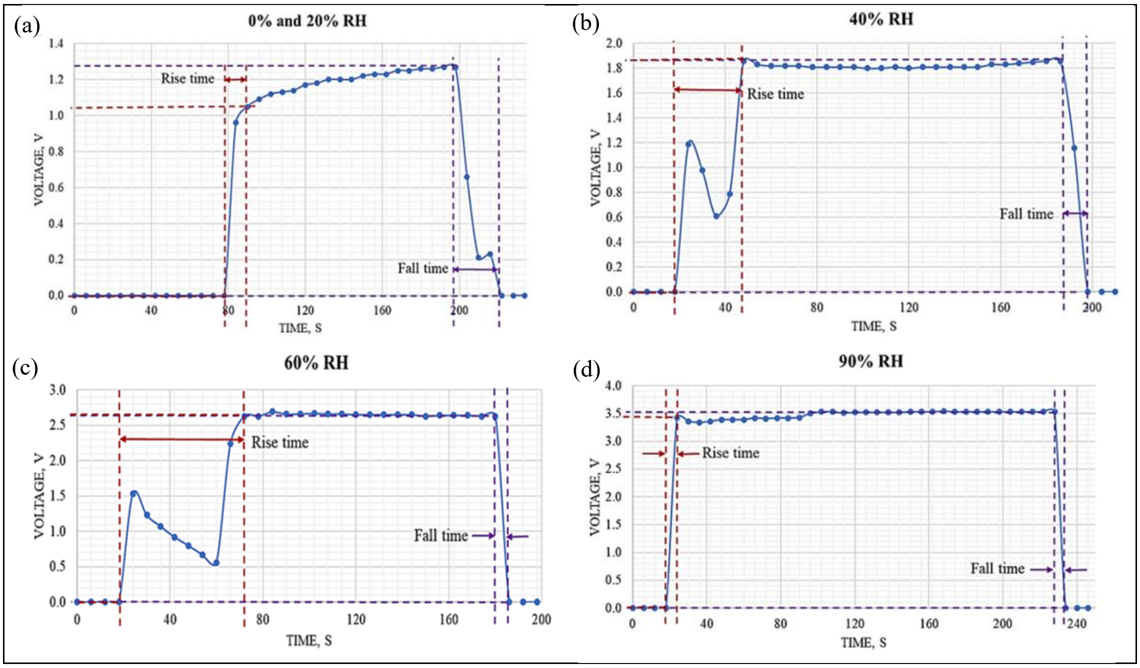

Fig. 10. Response time of ABTEST-03 sensor at (a) 0% to 20% (b) 40% (c) 60% and (d) 90% relative humidity.

In practical applications, various external factors may significantly impact the precision and reliability of resistivity-based soil moisture sensors. Soil composition variations, encompassing organic matter and ion concentration, directly influence conductivity and may result in inconsistent results without regular calibration. Environmental factors, like temperature and ambient humidity as well as soil salinity can modify sensor responses, as variations affect the dielectric characteristics of soil and expedite probe degradation (Qi et al., 2024; Gómez-Astorga et al., 2024; Yazdanpanah et. al, 2025). Moreover, prolonged exposure to fluctuating field conditions may result in noise and drift in data. Mitigating these problems necessitates regular recalibration, protective coatings, and algorithmic compensating mechanisms to guarantee dependable performance in precision agriculture applications (Mane et al., 2024).

Table 5 provides a quantitative comparison of the three resistive soil-moisture sensors assessed in this work, in conjunction with findings documented in prior literature. The ABTEST-01 exhibited the greatest sensitivity (0.0535 V/%RH), owing to its gold-plated electrodes that improve electrical conductivity and reduce corrosion. The ABTEST-01's enhanced sensitivity allows it to identify little changes in soil moisture, despite moderate voltage fluctuations noted at mid-range humidity levels. The ABTEST-01 and ABTEST-02 sensor demonstrated a rapid response time (6–30 s), signifying effective charge transfer and swift detection capability, rendering it appropriate for applications necessitating dynamic moisture monitoring. Simultaneously, the ABTEST-03 sensor, featuring an integrated LM393 comparator, demonstrated remarkable voltage stability and noise attenuation, yielding a highly stable even with less sensitive output (0.0387 V/%RH).

In comparison to previous research by Cappelli et al. (2023), Vivek et al. (2021), Borges et al. (2024) and Puengsungwan (2020), the current findings demonstrate significant enhancements in sensor responsiveness, stability, and integration dependability. The ESP32–Blynk IoT setup improved data

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acquisition and minimized signal drift, underscoring the benefits of optimized electrode design and interface circuitry. According to the authors' knowledge, there are a very limited number of research papers that thoroughly characterize commercial resistive soil-moisture sensors while simultaneously exhibiting complete system integration with a microcontroller platform. This study offers a significant reference for enhancing cost-effective IoT-based soil monitoring systems via quantitative performance evaluation.

Table 5. Quantitative performance comparison of resistive soil moisture sensors with previous studies, highlighting improvements in sensitivity, voltage stability, and response time for the current IoT-based experimental setup

Sensor type	Sensitivity (V/%RH)	Stability (voltage fluctuation)	Response time (s)	Key feature	Remarks/limitation
ABTEST-01 (This research)	0.0535	Moderate	6 - 30	High sensitivity, gold-plated probes	ESP32/Less stable at mid-RH
ABTEST-02 (This research)	0.0489	Moderate–Good	6 - 30	Fastest response time	ESP32/Moderate corrosion resistance
ABTEST-03 (This research)	0.0387	Excellent	6 - 54	Stable output with LM393 comparator	ESP32/Low sensitivity
Stainless-steel electrodes resistive moisture sensor Cappelli et al. (2023)	Not directly expressed in V/%RH terms	Moderate	Not reported	Demonstrating high sensitivity within 100 Hz–100 kHz	Prone to electrode oxidation and chemical drift.
Copper sheet - Soil resistivity sensors Vivek et al. (2021)	Not explicitly stated	Moderate	No data provided	Cost-effective design	ESP8266 / Affected by corrosion, Resistive sensors are strongly soil-dependent (texture, salinity, ionic content), so site-specific calibration is required
Resistive zinc probes Puengsungwan (2020)	No data provided	Moderate	No data provided	Sensitive to salinity	ESP8266 / Acceptable output
HL-69-resistive soil moisture sensor Borges et al. (2024)	No data provided	Moderate	~600 s (10 min stabilization time before steady reading)	Low-cost, simple analog output, easy calibration	Slow moisture diffusion, limited stability

CONCLUSION

In conclusion, the objectives of the research on the characterization of moisture sensors for the IoT-based real-time monitoring system were successfully achieved by evaluating multi-point soil moisture data from each sensor in real-time, analyzing the performance of various types of soil moisture sensors, and developing a soil moisture monitoring system integrated with an IoT-based application. The created prototype design could be extensively utilized as a sub-component in smart agriculture applications. The findings suggest that different types of soil moisture sensors respond differently to variations in soil relative humidity levels. The ABTEST-03 sensor exhibited the most voltage stability performance. Concurrently, the ABTEST-01 sensor was identified as the optimal sensor for sensitivity performance due to its superior sensitivity value, 0.0535 V/%RH. Conversely, the ABTEST-02 sensor exhibited the fastest response time, flourished by the ABTEST-01, while the ABTEST-03 demonstrated the slowest response time. Consequently, the selection of suitable sensors is crucial, since the attributes of various moisture sensors will influence the advancement of a monitoring system for soil moisture using IoT technology, depending on the specific requirements of the systems and applications. In addition to smart agriculture, these IoT-

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based resistive sensors facilitate environmental monitoring, greenhouse humidity regulation, soil research in controlled environments, and urban landscaping systems, where real-time moisture data enhances water conservation and plant healthy growth. Furthermore, the suggested technology provides economic viability via inexpensive resistive sensors and ESP32 microcontrollers. Its modular IoT architecture facilitates scalability for multi-node deployment across extensive agricultural fields with minimal infrastructural expenditure.

For future work recommendation, other types of commercially available sensors could be characterized as well, such as the capacitive or impedance-based moisture sensors. This suggestion could be used to investigate the properties and behaviour of additional commercially available sensors with broad uses in agriculture. Furthermore, the proposed soil moisture monitoring system might be tested by merging other recent and updated IoT software to create a more user-friendly graphical user interface (GUI). In the future, an enhanced version, such as Arduino IoT software, could replace the Blynk 2.0 platform for GUI design and the Arduino IDE for coding. This may improve the process of constructing monitoring system visualization since the construction of programming code and the design layout of the GUI are both available on the same platform. Aside from that, instead of using a power bank, the device might be outfitted with photovoltaic solar cells as its power source. As a result, the system may minimize energy usage while also meeting the Sustainable Development Goal (SDG) of incorporating sustainable energy sources. Finally, this proposed technology might be combined with a smart irrigation system to provide water to crops at an economical and appropriate rate. When utilized in other smart systems for precision agriculture (PA) applications, the behaviour of the various sensor types can be closely monitored and evaluated.

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CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

AUTHORS' CONTRIBUTION

The authors confirm their contribution to the paper as follows: Writing – original draf & editing: Wan Nur Sabrina Wan Ahmad Aziz, Rozina Abdul Rani. Writing – review: Rozina Abdul Rani, Ahmad Sabirin Zoolfakar, Maizatul Zolkapli, Dharma Aryani. Data Collection: Wan Nur Sabrina Wan Ahmad Aziz, Rozina Abdul Rani. Supervision & Funding acquisition: Rozina Abdul Rani, Ahmad Sabirin Zoolfakar. Result analysis and validation: Wan Nur Sabrina Wan Ahmad Aziz, Rozina Abdul Rani, Ahmad Sabirin Zoolfakar, Maizatul Zolkapli, Dharma Aryani.

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