Performance curve of two analog sensors for estimating soil moisture

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ABSTRACT

Objective: This study aims to assess the influence of two distinct soil textures on the performance of commercial soil moisture sensors specifically, the WaterScout SM100 and Vegetronix VH400 in measuring volumetric soil water content.

Design/Methodology/Approach: A triplicated laboratory experiment was conducted using two prevalent soil textures from Zacatecas: sandy and loam. Sensor responses to varying moisture levels were recorded and analyzed through linear regression models, with model fit evaluated using the coefficient of determination (R^2).

Results: Both sensors demonstrated a strong linear response in sandy soils (R^2=0.98 for both Vegetronix and WaterScout). In loam soils, the linearity remained high for the Vegetronix sensor (R^2=0.98) but was moderately reduced for the WaterScout (R^2=0.89). These outcomes underscore the significant effect of soil texture on sensor accuracy.

Limitations/Implications: The scope of the study was confined to two soil textures and did not consider additional variables such as salinity or temperature, which could also influence sensor performance. The results underscore the necessity of site-specific calibration to enhance measurement reliability.

Findings/Conclusions: Soil texture plays a crucial role in the accuracy of moisture sensor readings, with direct implications for irrigation scheduling. Consequently, we advocate for the development of localized calibration protocols to optimize sensor performance and irrigation efficiency.

Keywords: Water control, soil moisture sensors, soil texture, irrigation management, calibration.

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INTRODUCTION

The use of water resources poses critical challenges for modern agriculture. Climate change, water scarcity, and the increasing demand for food have driven the development of precision agriculture strategies aimed at maximizing productivity through the efficient use of inputs such as water and energy (Ahmed *et al.*, 2025; Tornese *et al.*, 2024). The integration of the Internet of Things (IoT) has facilitated the creation of monitoring systems capable of collecting, transmitting, and analyzing real-time data through microcontrollers such as the ESP32 (Saputra & Suryono, 2025). Soil moisture sensors are employed as key tools for real-time monitoring of soil water content, enabling more efficient, data-driven irrigation

management (Abdelmoneim *et al*., 2024; Marino *et al*., 2023). However, the performance of these sensors can vary significantly depending on soil texture and environmental conditions, underscoring the necessity for proper calibration and validation procedures (Hidayat *et al*., 2024). A lack of calibration can result in inaccurate measurements, ultimately compromising irrigation efficiency. Furthermore, conventional calibration methods are often labor-intensive and susceptible to human error, which limits their large-scale adoption (Schwamback *et al*., 2023). In response to these challenges, the main aim of this study was to evaluate the performance of two soil moisture sensors WaterScout SM100 and Vegetronix VH400 under controlled conditions using an ESP32 microcontroller. The drying process of the soil was monitored, moisture content was determined, and the performance of both sensors was compared across two soil textures: loam and sandy.

MATERIALS AND METHODS

Study area

The study was conducted in the irrigation laboratory at the Zacatecas Experimental Field (Campo Experimental Zacatecas, CEZAC) of the National Institute for Forestry, Agricultural and Livestock Research (Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, INIFAP), located at kilometer 24.5 of the Zacatecas-Fresnillo highway (22° 45’ N, 102° 39’ W), at an elevation of 2,197 meters above sea level. The site has an average annual temperature of 14.6 °C and accumulates approximately 600 chilling units (CU) between November and February. Annual precipitation averages 416 mm, with 75% occurring during the summer months (June-September), while annual evaporation reaches 1,609 mm.

Soil texture

Two soil textures representative of agricultural areas surrounding the CEZAC were selected for this study (Table 1). The physical characteristics of the selected soils correspond to a sandy soil and a loam soil (Figure 1).

Soil moisture measurements

The soil was air-dried outdoors at an average temperature of approximately 35 °C for a period of seven days. For each soil type, three plastic containers with a volume of 61.52 L were filled, adding 45 kg of loam soil and 50 kg of sandy soil per container. Initial soil moisture content was determined to calculate the dry weight of the soil. The weight of each container was measured using a scale with a maximum capacity of 200 kg and an accuracy of 1 g (BAS-200PLA, Truper, USA). The tare weight was adjusted to account for the mass of the moisture and temperature sensors. For saturation, the containers were

Table 1. Characteristics of two typical soils used for agricultural purposes in Zacatecas.

Texture	Sand (%)	Clay (%)	Silt (%)	Organic Matter (%)	Bulk Density (g cm^{-3})
Sandy	65.8	12.2	22.0	0.67	1.56±0.089
Loam	37.8	30.2	32.0	2.33	1.24±0.062

Note: Organic Matter (OM), Bulk Density (BD).

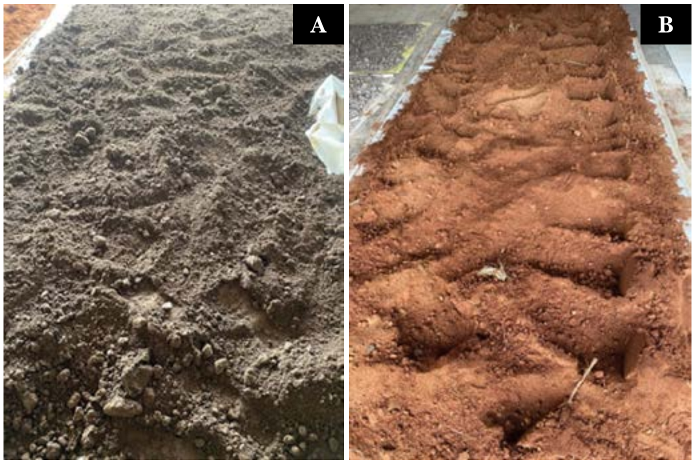

Figure 1. Visual characteristics of the soils used: (A) Loam soil, (B) Sandy soil.

placed in a waterproof tank measuring 2×2 m^2 and were partially submerged in water, allowing moisture absorption through the drainage holes at the base by capillary action until saturation was reached (Figure 2A). Afterward, the containers were removed and allowed to drain for 12 hours to eliminate excess water. The weight of the water absorbed during saturation was recorded, ensuring homogeneous conditions for monitoring both soil weight and moisture content (Figure 2B). The soil was then left to dry at room temperature until it reached a constant weight. During this drying period, sensor readings and the total weight of each container (Soil+Tare+Water) were recorded at one-minute intervals. Additionally, the weight of the moist soil defined as the weight of the soil plus wáter was used to calculate the gravimetric soil moisture (%) using the following equation:

$$\%SM = \frac{W_{wet} - W_{dry}}{W_{dry}} \times 100 \tag{1}$$

Where: $\%SM$ is the gravimetric soil moisture expressed as a percentage, W_{wet} is the weight of the moist soil, and W_{dry} is the weight of the dry soil.

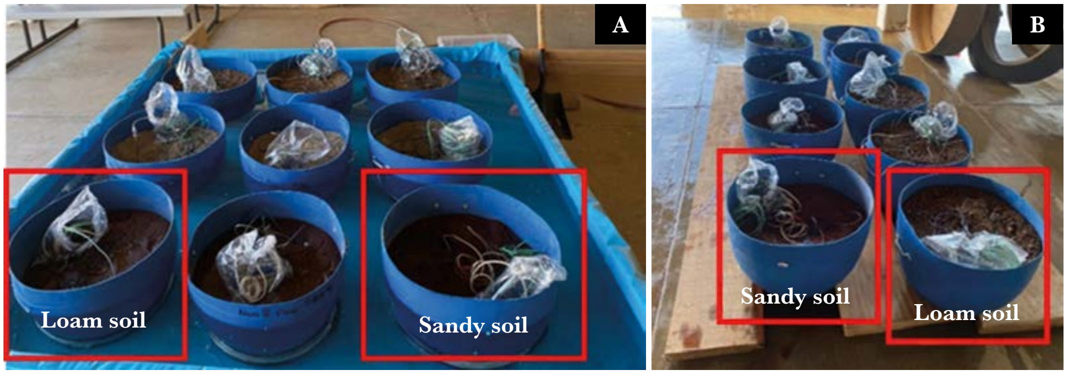

Figure 2. Soil saturation and drainage process in containers. (A) Soil saturation in a waterproof tank, (B) drainage of excess water from the containers.

Data acquisition

Two analog sensors WaterScout (SM100, Spectrum Technologies, USA) and Vegetronix (VH400, Vegetronix, Inc., USA) were used to estimate soil moisture by correlating it with voltage readings recorded by a microcontroller. A 300 kg load cell, coupled with an HX711 module that converts analog signals to digital format, was employed to measure the container's weight and estimate water loss.

Sensor and load cell readings were handled by an ESP32 microcontroller, which processed and transmitted real-time data on sensor voltage, temperature, and soil weight. This setup is illustrated in Figure 3. The automated recording process operated in defined cycles. Initially, the EEPROM memory was configured to establish the baseline weight, the balance was calibrated, and a watchdog timer was activated to prevent system crashes during data acquisition.

Data were saved to a microSD card in CSV format and simultaneously transmitted to a Google Sheets platform via Wi-Fi. To optimize energy consumption, the ESP32 entered a deep sleep mode between cycles, reactivating every minute to repeat the monitoring process.

Data analysis

Soil weight data were converted into moisture percentages and correlated with sensor readings in millivolts (mV). Since the relationship between these variables was not strictly linear, a polynomial regression model was applied to enhance the accuracy of the fit. The degree of the polynomial was selected based on the highest coefficient of determination (R^2), which quantifies the proportion of variability in the sensor readings explained by changes in soil moisture. Data preprocessing was conducted using the R statistical software, version 3.0.2, and subsequent analyses were performed in Microsoft Excel. Built-in regression tools were used to estimate the model parameters and their corresponding R^2 values.

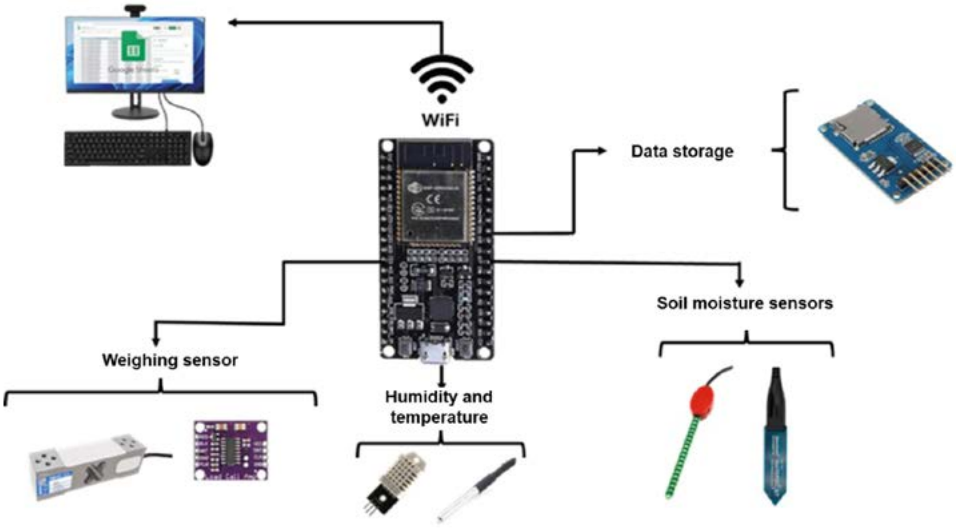

Figure 3. Schematic of the monitoring and data acquisition system.

RESULTS AND DISCUSSION

Figure 4 illustrates the differences in drying rates between the two soil types evaluated. The loam soil exhibited a weight reduction from 58,615 g to 51,298 g, whereas the sandy soil decreased from 62,468 g to a minimum of 55,620 g over the drying period. In absolute terms, the loam soil lost 7,317 g of water, corresponding to 12.48% of its initial weight. In contrast, the sandy soil lost 6,848 g, equivalent to 10.96%. These findings indicate that loam soil promotes greater water evaporation compared to sandy soil, likely due to its higher water retention capacity. Since the experiment was conducted under controlled laboratory conditions, water loss can be solely attributed to evaporation, excluding influences such as drainage or plant uptake.

The slope of the drying curves indicates that soil texture directly influences both the rate of moisture loss and the maximum water retention capacity. Sandy soil exhibited lower water retention compared to loam soil, which can be attributed to its lower content of fine particles. This difference is associated with variations in pore size distribution: sandy soils, characterized by larger pores, facilitate higher hydraulic conductivity and consequently faster evaporation rates (Negyesi *et al.*, 2021). These findings underscore the importance of considering soil texture when interpreting moisture sensor readings, as drying dynamics can significantly affect data accuracy and its applicability in irrigation monitoring systems. Measurements obtained with the Vegetronix VH400 sensor revealed texture-dependent differences in sensor response, with steeper slopes observed in sandy soils than in loam. In both cases, a general downward trend in voltage was recorded throughout the drying period, reflecting the gradual loss of soil moisture. However, Figure 5 illustrates distinct drying dynamics: in sandy soils, which contain a higher proportion of coarse particles, the voltage decreased uniformly and across a broader range compared to loam soils. In contrast, Figure 6 shows the performance of both sensors in soil with a higher content of fine particles. The sensor response exhibited greater variability, with more pronounced fluctuations and a slower decline in voltage readings compared to sandy soil. This behavior suggests higher moisture retention and internal redistribution of water within the soil profile, delaying the overall moisture loss.

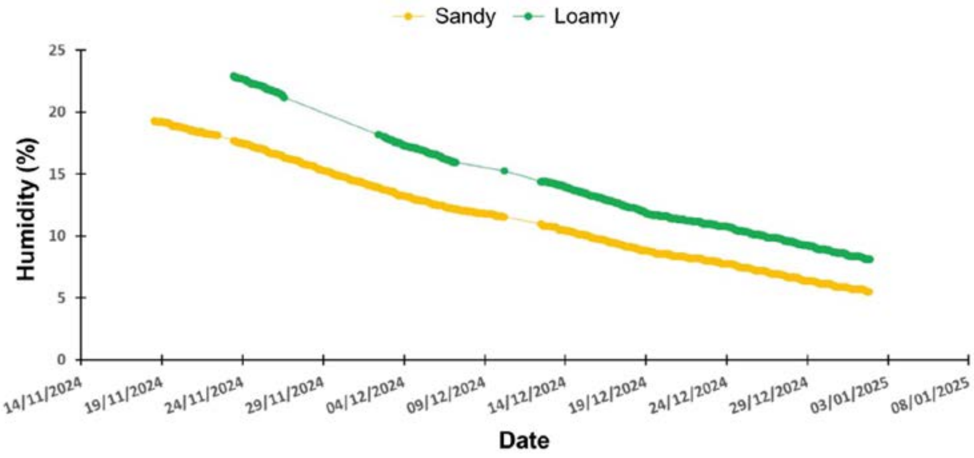

Figure 4. Soil drying dynamics over time for different textures.

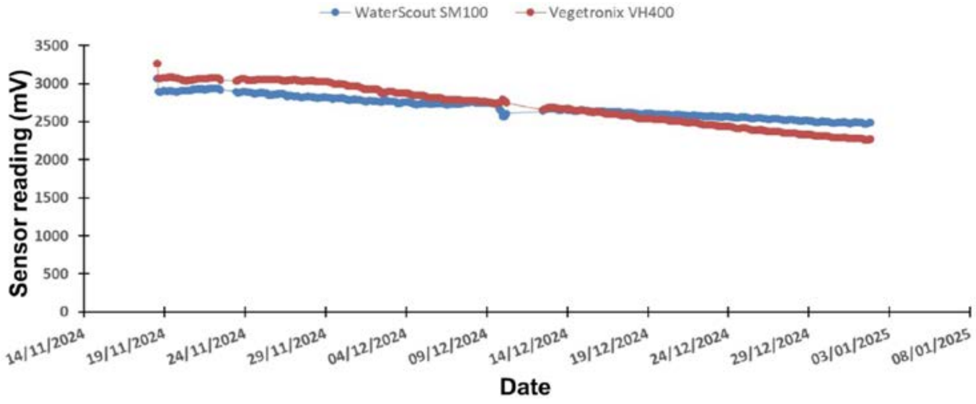

Figure 5. Sensor response of Vegetronix VH400 and WaterScout SM100 over time in sandy soil textures.

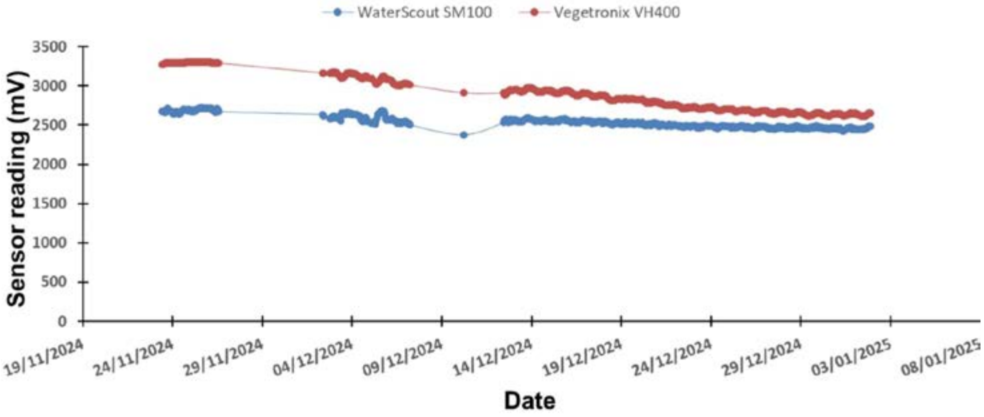

Figure 6. Sensor response of Vegetronix VH400 and WaterScout SM100 over time in loam soil textures.

These differences can be attributed to the influence of bulk density and soil porosity on hydraulic conductivity and water distribution. In more compact soils, water is retained for longer periods, affecting sensor measurements and delaying voltage stabilization (Teixeira & Correia, 2021). In Figure 5, which corresponds to the soil with a higher proportion of coarse particles (sandy texture), the voltage decreases progressively and relatively steadily, with minor interruptions in the trend that may indicate adjustments in internal water redistribution within the sample. In contrast, in loam soil characterized by a higher content of fine particles (Figure 6) the sensor signals exhibit greater variability and abrupt fluctuations throughout the monitoring period. These anomalies may be partially attributed to fluctuations in the electrical network; however, the overall drying trend remains consistent.

Figure 6 presents the measurements obtained with the WaterScout SM100 sensor in loam soil, revealing notable differences in sensor response compared to sandy soil conditions (Figure 5). In both cases, a general downward trend in voltage is observed throughout the drying period, reflecting the decline in soil moisture content. Nevertheless, the magnitude and stability of the readings vary significantly between soil textures.

These differences may be due to the interaction between soil porosity and the sensor's dielectric response. In soils with higher clay or silt content, water retention in micropores can cause localized variations in electrical conductivity, thereby affecting the stability of sensor readings (Yu *et al.*, 2021). Furthermore, soil compaction may alter the distribution of water within the soil matrix, resulting in abrupt changes in measurement values. The relationships between sensor outputs and weight loss over time for each soil type are presented in Figures 7 and 8. Both the VH400 and SM100 sensors exhibited a linear response to weight loss in both soil types. According to the polynomial regression models, the SM100 sensor in loam soil achieved an R^2 of 0.89, while all other linear relationships demonstrated excellent fits with R^2 values exceeding

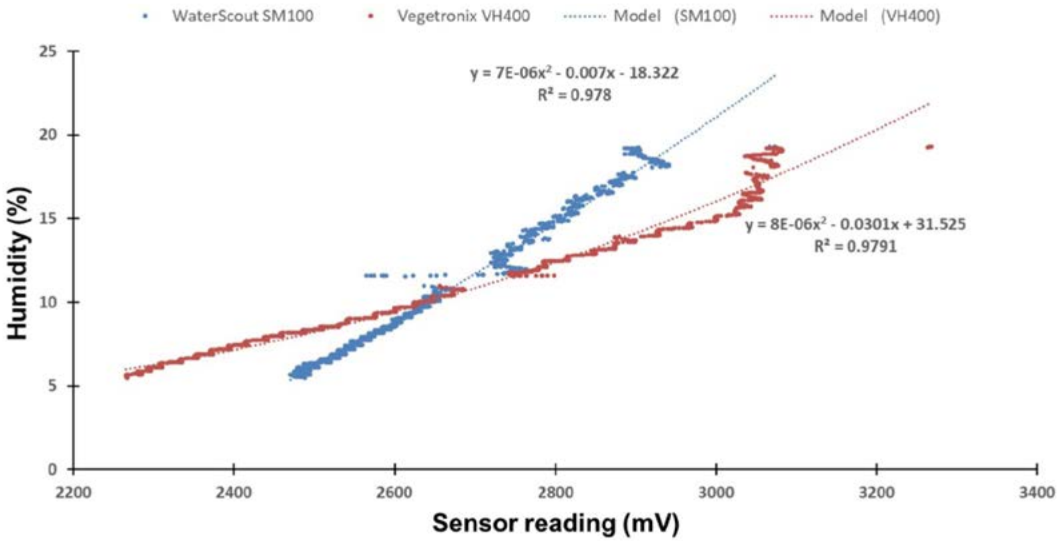

Figure 7. Sensor response of Vegetronix VH400 and WaterScout SM100 in sandy soil textures.

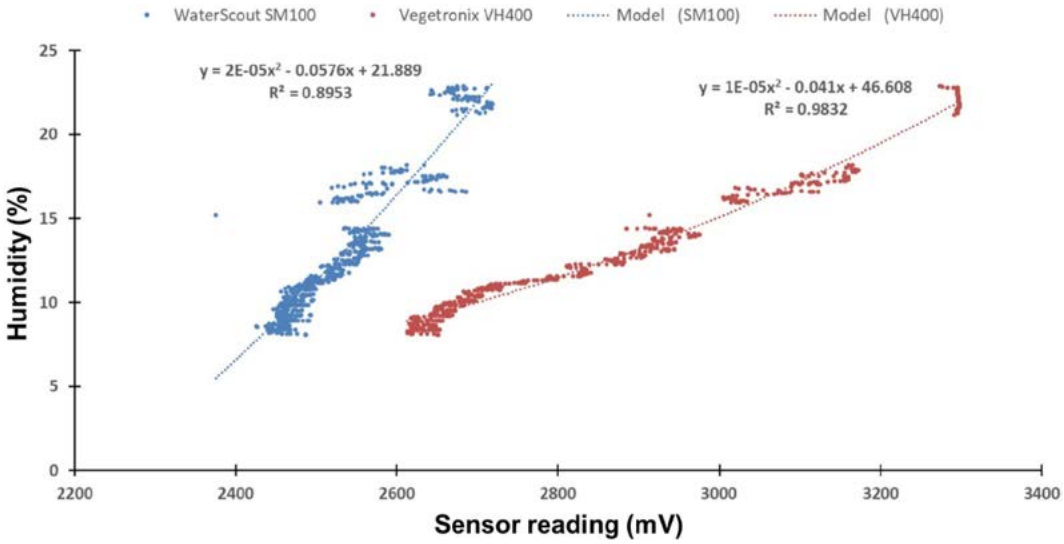

Figure 8. Sensor response of Vegetronix VH400 and WaterScout SM100 in loam soil textures.

0.97. The p-values indicate the statistical significance of both the slope and intercept in the linear relationships. All slopes and intercepts were highly significant across both soil textures ($P<0.001$). These results confirm that both sensors responded effectively to changes during the soil drying process.

Soil moisture measurement techniques based on capacitance rely on the high dielectric constant of free water (∼80) compared to that of dry soil, which typically ranges from 1.5 to 4 (Maliyetli *et al.*, 2024). This contrast causes variations in the overall dielectric constant of the soilwater-air mixture as soil moisture content changes. Although moisture is the primary factor influencing this constant, other parameter such as salinity, organic matter content, and bulk density can also affect sensor responses (Hidayat *et al.*, 2024).

Variations in sensor output may stem from differences in the intrinsic dielectric properties of soil particles, as well as soil compaction and the distribution of water within the soil matrix (Yuan *et al.*, 2024). These findings emphasize the importance of accounting for soil texture and bulk density when calibrating moisture sensors, particularly in agricultural applications where measurement accuracy is critical for effective irrigation management. The findings of da Silva *et al.* (2018) confirm that sensor accuracy and stability vary by soil type. While sensors such as the Porous Cup Tensiometer, ML3, Diviner 2000, and PR2 reported errors below 5% and R^2 values above 0.95, the performance of XH300 and PM100 sensors was less reliable, with R^2 values ranging from 0.37 to 0.94. These results highlight the influence of soil properties on sensor performance and the necessity of developing sensor- and soil-specific calibration curves, as generalized calibrations may not be applicable across different substrates.

CONCLUSIONS

The two sensors evaluated in this study (WaterScout SM100 and Vegetronix VH400) demonstrated significant responsiveness to changes in soil water content. Both SM100 and VH400 exhibited linear responses. However, sensor performance was significantly influenced by soil texture, which in turn could affect the activation of irrigation systems based on sensor readings. To enhance measurement accuracy, it is recommended to perform site-specific calibrations tailored to local conditions. Additionally, the development of localized technical guidelines would be valuable to support the proper use of these sensors in irrigation scheduling, thereby promoting efficient water management.

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