Calibration and Temperature Compensation of a Low-Cost Capacitive Soil Moisture Sensor for Precision Irrigation in Thailand

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ABSTRACT

Low-cost capacitive soil moisture sensors have potential application in precision irrigation in Thailand. However, these sensors require proper calibration and are affected by soil temperature fluctuations that reduce their measurement accuracy. This study developed and validated a combined calibration and temperature compensation approach for the commercially available soil stick sensor. The calibration was performed using soil samples ranging from sandy clay loam to silty clay. A temperature compensation equation was developed by measuring the sensor responses under varying soil temperatures and moisture content levels in outdoor conditions. The sensor performance was assessed against a reference Time-Domain Reflectometry (TDR) sensor (TRIME-PICO64) and evaluated based on continuous field measurements for 14 days. The temperature compensation equation reduced the diurnal temperature effects through a linear correction model. The calibration showed a piecewise linear relationship between the Relative Voltage (V_R) and volumetric water content (θ_V) with a strong correlation. The performance of the calibrated soil stick sensor was comparable to the TDR sensor, with the Confidence Index values exceeding 0.8. These findings indicated that the calibrated and temperature-compensated low-cost capacitive sensors could provide accurate soil moisture measurements for precise irrigation scheduling.

Keywords-low-cost capacitive soil moisture sensor; temperature compensation; precision irrigation

I. INTRODUCTION

Water scarcity is a major global challenge, resulting from an increased water demand due to the population growth and economic development. Improving irrigation efficiency is critical to mitigate this impact [1]. Recent technological advances in precision irrigation systems have enabled more efficient water management through real-time monitoring sensors, allowing accurate determination of irrigation requirements [2]. Soil moisture sensors are essential components for water content monitoring in irrigation systems. Among these, dielectric soil moisture sensors, which utilize the difference in dielectric permittivity between water and other soil components, have emerged as essential tools for soil moisture monitoring [3]. TDR sensors are known for their high accuracy; however, their high cost limits their widespread use [4]. Capacitive soil moisture sensors, another type of dielectric sensor, offer a cost-effective alternative due to their rapid response to soil moisture changes and durability. These sensors typically measure the θ_V of the soil, expressed in $cm^3\ cm^{-3}$, representing the water volume ratio to the total soil volume [5]. This measurement is crucial for irrigation scheduling as it directly relates to the water available to plants in the soil. However, these sensors are susceptible to the soil properties and temperature fluctuations, constraining their effectiveness in precision irrigation [6, 7]. Addressing the limitations of low-cost capacitive sensors requires both soil-specific calibration and temperature compensation to ensure an accurate soil moisture measurement for precision irrigation applications. This study focused on developing calibration and temperature compensation equations for agricultural soils. The calibration equation was evaluated against a reference soil moisture sensor, while the temperature compensation equation was validated under field conditions. These advancements should improve the reliability of low-cost sensors for precise irrigation scheduling in agricultural communities.

II. MATERIALS AND METHODS

A. Soil Sampling and Soil Property Analysis

Ten soil samples were collected from agricultural areas in Phetchaburi province, Thailand. The soil samples were classified based on hydrometric analysis to determine their texture. The hydraulic properties of the soil, including the volumetric water content at Field Capacity (θ_{FC}) and permanent wilting point (θ_{PWP}), were estimated using the method presented in [8]. The analysis results are presented in Table I. The soil samples had θ_{FC} values ranging from 0.19 $cm^3\ cm^{-3}$ to 0.45 $cm^3\ cm^{-3}$, θ_{PWP} values ranging from 0.09 cm^{-3} to 0.25 cm^{-3}, and bulk density (ρ_b) values ranging from 1.22 $g\ cm^{-3}$ to 1.47 $g\ cm^{-3}$. These soil samples were utilized for various experiments. PB01 was utilized to determine the temperature compensation equation, PB02–PB08 were used for sensor calibration, and PB09 and PB10 were used to evaluate the performance of the calibrated sensor.

TABLE I. PROPERTIES OF SOIL SAMPLES

Sample	Sand (%)	Clay (%)	Texture	ρ_b ($g\ cm^{-3}$)	θ_V ($cm^3\ cm^{-3}$)	
					θ_{FC}	θ_{PWP}
PB01	64.43	17.72	SL	1.47	0.19	0.09
PB02	54.53	27.30	SCL	1.39	0.24	0.13
PB03	27.26	32.21	CL	1.31	0.32	0.15
PB04	9.94	33.21	SiCL	1.45	0.45	0.15
PB05	43.93	37.65	CL	1.32	0.29	0.17
PB06	14.77	51.05	C	1.41	0.40	0.23
PB07	8.42	41.03	SiC	1.24	0.38	0.19
PB08	18.17	55.37	C	1.22	0.40	0.25
PB09	61.44	29.98	SCL	1.42	0.23	0.14
PB10	39.46	43.22	C	1.41	0.32	0.20

SL = sandy loam, SCL = sandy clay loam, CL = clay loam, SiCL = silty clay loam
C = clay, SiC = silty clay

B. Temperature Compensation of Capacitive Soil Moisture Sensor

This study utilized the soil stick sensor (DO IN THAI Co., Ltd., Thailand), an affordable, uncalibrated capacitive soil moisture sensor available in Thailand, as illustrated in Figure 1. In addition to measuring soil moisture, the soil stick sensor can record temperatures (°C). Previous studies on temperature compensation have shown that the corresponding equations follow a linear trend in the same direction [9-11]. The general form of these equations is:

$$V_O = V_S - \alpha(T_S - T_O) \quad (1)$$

where V_O is the voltage output at the reference temperature (mV), V_S is the voltage output at the measured soil temperature (mV), T_S is the measured soil temperature (°C), T_O is the reference temperature (°C), and α is the slope value (mV/°C).

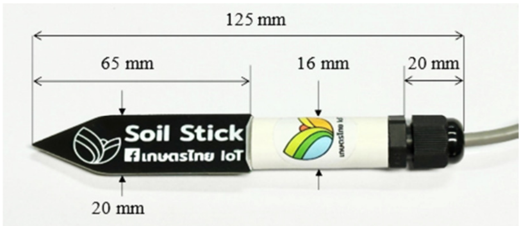

Fig. 1. Soil stick sensor.

Sandy loam soil (PB01) was selected for the temperature compensation experiments. The sensor was tested at five different moisture content levels (0.21 $cm^3\ cm^{-3}$, 0.28 $cm^3\ cm^{-3}$, 0.35 $cm^3\ cm^{-3}$, 0.43 $cm^3\ cm^{-3}$, and 0.52 $cm^3\ cm^{-3}$). The experiment was conducted in clear acrylic cylinder containers with lids, having an inner diameter of 9 cm and a height of 20 cm (the optimal height was 13 cm). The soil stick sensors were installed through a hole in the lid and then sealed to prevent soil evaporation. This process was performed outdoors to measure the soil temperature (T_S) and the voltage (V_S) for 7 days, as shown in Figure 2(a). Finally, the relationship between T_S and voltage output (V_O) was analyzed to determine the value of α for each soil moisture range.

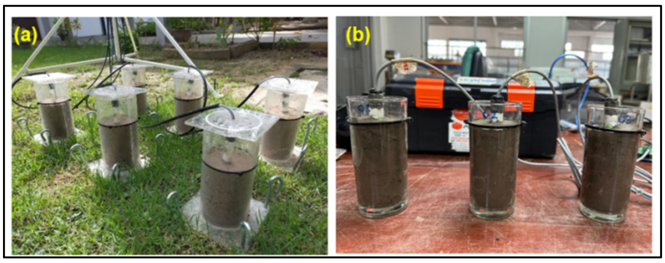

Fig. 2. Experimental setup for: (a) temperature compensation and (b) sensor calibration.

C. Capacitive Soil Moisture Sensor Calibration

To calibrate the equation, laboratory experiments were conducted under a controlled temperature of 27±1 °C to regulate the influence of T_S. The calibration determined the relationship between the soil stick sensor's V_R and the volumetric water content (θ_V). The V_R was calculated to normalize the V_o on a percentage scale to minimize the differences between the sensors. Based on a normalization approach [12], the V_o measured in distilled water and dry air determined the ranges for the upper and lower voltage outputs. These ranges correspond to the dielectric permittivity (ε) of water (ε ≈ 81) and air (ε ≈ 1), representing the maximum and minimum values under soil conditions. The formula is:

$$V_R(\%) = 100 - \left(\frac{V_O - V_{water}}{V_{air} - V_{water}} \times 100\right) \quad (2)$$

where V_{air} is the voltage output measured in dry air (mV), and V_{water} is the voltage output measured in pure water (mV).

The volumetric water content of soil (θ_V) can be determined by the weighing method [5]:

$$\theta_V = \frac{V_w}{V_t} = \frac{\rho_b}{\rho_w} \times \frac{m_w}{m_s} \quad (3)$$

where θ_V is the volumetric water content of soil ($cm^3\ cm^{-3}$), ρ_b is the bulk density of the soil ($g\ cm^{-3}$), ρ_w is the density of water ($g\ cm^{-3}$), V_w is the volume of water in soil (cm^3), V_t is the bulk volume of soil (cm^3), m_w is the mass of water in soil (g), and m_s is the mass of dry soil (g).

Assuming ρw was 1 $g\ cm^{-3}$, the weight of the oven-dried soil sample and distilled water was determined as a direct measurement sample in a clear glass container with an inner diameter of 6 cm and a height of 13 cm (the optimal height was 11 cm). Each oven-dried soil sample was mixed with water until the soil moisture was uniformly distributed and then packed into the container to an optimal height to control the soil's ρb. The moisture content of three replicate soil samples was measured using a soil stick sensor, as shown in Figure 2(b). The measured values from the three replicate samples were averaged to obtain a representative V_O. The three soil stick sensors were connected to a NodeMCU ESP32 microcontroller, operating at 3.3 V. However, the soil stick sensor has a regulator circuit that maintains a constant 3 V input voltage. V_O was measured at different θ_V values of the soil in the container. The process was conducted across a moisture range from θ_{PWP} to θ_{FC} for each type of soil sample. Finally, the relationship between V_R and θ_V was fitted using a calibration equation.

D. Performance of Temperature-Compensated and Calibrated Low-Cost Capacitive Soil Moisture Sensor

To assess the performance of the soil stick sensor compared to the TRIME-PICO64 sensors (IMKO Micromodultechnik GmbH, Germany), which are TDR sensors based on the equation for universal soil moisture measurement from [13], a laboratory experiment was conducted using two soil samples: PB09 (Sandy Clay Loam) and PB10 (Clay). The evaluation metrics included the Coefficient of Determination (R^2), Root Mean Square Error (RMSE), Pearson's Correlation Coefficient (r), Willmott's Index of Agreement (d), and the Confidence Index (CI) [14, 15]. These metrics are defined in:

$$R^2 = \frac{\sum_{i=1}^{n}(P_i - \bar{O})^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (4)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \quad (5)$$

$$r = \frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}} \quad (6)$$

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2}\right] \quad (7)$$

$$CI = r \times d \quad (8)$$

where n is the number of data points, P_i is the soil moisture content measured by the sensor, $\bar{P}$ is the averaged soil moisture content measured by the sensor, O_i is the soil moisture content by direct measurement, and $\bar{O}$ is the averaged soil moisture content by direct measurement. CI reflects performance as follows: CI > 0.85 indicates excellent performance, 0.76–0.85 is very good, 0.66–0.75 is good, 0.61–0.65 is regular, 0.51–0.60 is unsatisfactory, and CI < 0.51 represents poor performance.

Following the established temperature compensation equation, a field experiment was conducted from April 1st to April 14th, 2023, under conditions without rainfall or irrigation. Measurements of V_S and T_S were collected every 15 min at the soil stick sensor station located in a silty clay soil area in Phetchaburi province, Thailand. The measured V_S values were corrected using the temperature-compensated V_R equation and were subsequently used in the calibration equation to calculate θ_V. To evaluate the influence of T_S on θ_V determination, a linear regression analysis was performed to examine the relationship between T_S and θ_V. The slope of the regression line was utilized as an indicator of this relationship. A slope value (α) approaching zero suggests an independent relationship between T_S and θ_V, indicating that the temperature has minimal influence on the determination of soil moisture using the calibration equation.

III. RESULTS AND DISCUSSION

A. Temperature Compensation and Calibration Equations

The temperature compensation equation results demonstrated a strong linear relationship between T_S and V_S across all moisture content levels, as portrayed in Figure 3. The R^2 values ranged from 0.988 to 0.998, indicating a high degree of correlation. Additionally, the slope values (α) remained consistent across different moisture levels, with values of 2.874 mV/°C, 2.891 mV/°C, 2.944 mV/°C, 3.048 mV/°C, and 3.010 mV/°C. Based on these findings, an average slope of 2.971 mV/°C was used to formulate the temperature compensation equation, as presented in (9). The reference temperature (T_0) was set at 27°C, reflecting typical laboratory conditions for soil moisture sensor calibration. Finally, (9) was combined with (2) to derive the temperature-compensated V_R, improving soil moisture estimation accuracy under varying field conditions:

$$V_O = V_S - 2.971(T_S - 27) \quad (9)$$

Regarding the calibration of the sensor with soil samples PB02–PB07, like previous findings [16], a piecewise linear relationship was found between the V_R and volumetric soil moisture content (θ_V), as shown in Figure 4. The breakpoint of the graph was at 94.76%, 0.248 cm³ cm⁻³. The linear equations for the two segments are:

$$\theta_{V1} = 0.0047V_R + 0.1973\,; V_R < 94.76\ \% \qquad (10)$$

$$\theta_{V2} = 0.0640V_R + 5.8166; V_R \geq 94.76\ \% \qquad (11)$$

A strong linear relationship existed between V_R and θ_V, with an R^2 value of 0.86. This result is comparable to previous findings [16], where piecewise linear relationships achieved R^2 values ranging from 0.82 to 0.95. Although different studies used non-linear calibration models, such as third-order polynomials, exponential, or sigmoidal functions, for various soil types [17-19], this study demonstrated that a straightforward piecewise linear calibration equation was suitable for sandy clay loam to silty clay soils. The calibration data from the soil sample PB08 were excluded due to its high clay content (>55%). This occurred because soils with a high clay content typically have a high Cation Exchange Capacity, disturb the bound water layers' molecular structure, and affect the dielectric measurement [20].

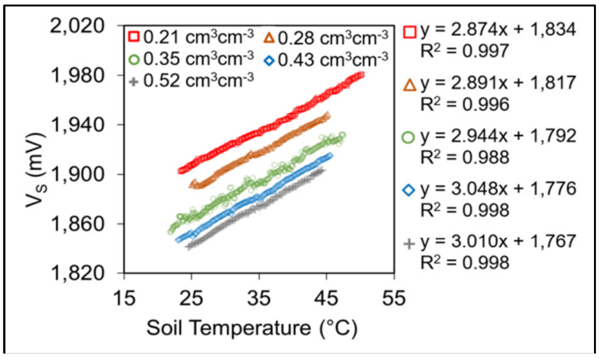

Fig. 3. Temperature-voltage relationships at different soil moisture contents.

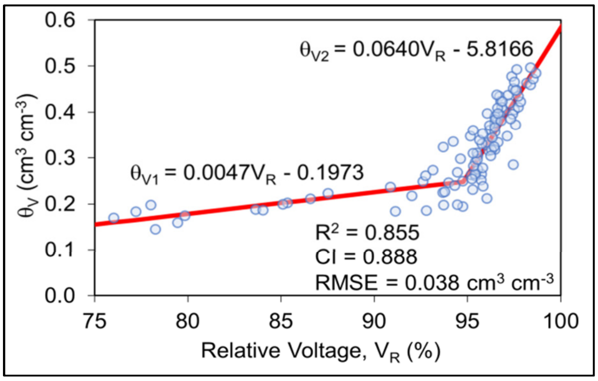

Fig. 4. Piecewise linear calibration of soil stick sensor.

B. *Performance of Calibrated, Low-Cost Capacitive Soil Moisture Sensor*

The performance of the calibrated Soil Stick and TRIME-PICO64 sensors was evaluated using soil samples PB09 (Sandy Clay Loam) and PB10 (Clay). Based on the results, the TRIME-PICO64 tended to overestimate the soil moisture, whereas the soil stick underestimated it, as demonstrated in Figure 5. In PB09, the soil stick exhibited good performance (CI = 0.830), whereas the TRIME-PICO64 displayed excellent performance (CI = 0.882). This pattern was reversed in PB10, where the soil stick achieved excellent performance (CI = 0.942), but the TRIME-PICO64 showed lower performance (CI = 0.717). For agricultural and research applications, sensors should achieve an RMSE of less than 0.04 cm³ cm⁻³ [21]. However, the TRIME-PICO64 sensors had higher RMSE values in clay-rich soils, consistent with the findings reported in [22]. This reflects the limitations of Topp's equation [13], which fails to provide accurate estimates in soils with a high clay content [23, 24]. The soil moisture measurements using the soil stick sensor in the field are depicted in Figure 6. The soil moisture content before temperature compensation fluctuated with diurnal temperature changes. In contrast, the compensated values gradually decreased, consistent with natural soil moisture loss. These results indicated that the temperature compensation equation effectively reduced the influence of the temperature variations on the soil moisture estimation, leading to more accurate assessments. Linear regression analysis was performed to examine the relationship between T_S and θ_V before and after temperature compensation, with the slope of the regression line having been used as an indicator of the temperature influence. Before compensation, the slope was -0.021, indicating a strong negative correlation between T_S and θ_V. This was consistent with the results reported in [25], where an increase in the T_S led to a decrease in the measured θ_V. After applying the temperature compensation equation, the slope was reduced to -0.001, demonstrating the effectiveness of the developed equation in minimizing temperature-induced errors in soil moisture measurement.

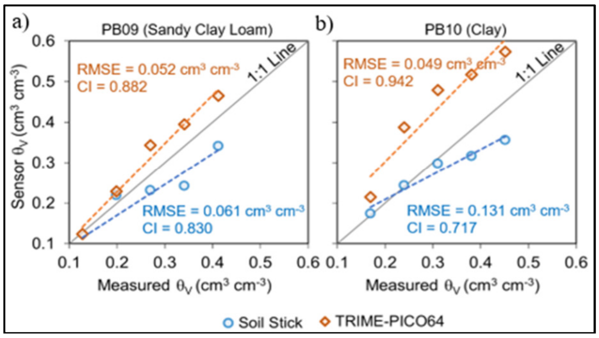

Fig. 5. Performance comparison of soil stick and TRIME-PICO64 sensors in (a) PB09 and (b) PB10 soils.

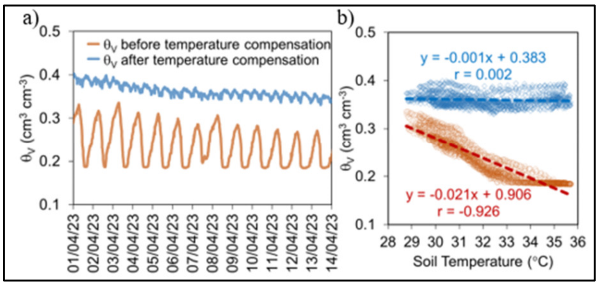

Fig. 6. Field measurement results: (a) soil moisture content before (showing fluctuations) and after (gradual decreasing trend) temperature compensation and (b) temperature-moisture relationships.

IV. CONCLUSIONS

This research has developed calibration and temperature compensation equations for soil stick sensors. The temperature compensation equation revealed a linear relationship with a reference temperature of 27°C. The calibration equation, developed using various soil types under laboratory conditions at 27°C, was a piecewise linear function. The calibrated soil stick sensor produced comparable results for the soil moisture measurements with those of a TDR sensor. Temperature compensation improved the accuracy of the measurements using the soil stick sensor. These findings demonstrated the potential of the calibrated and temperature-compensated soil stick sensor for use in precision irrigation systems. However, further research is needed to evaluate its long-term performance and impact on water use efficiency in real-world agricultural settings. Additionally, based on the current study, it is proposed that:

- If the sensor is used in agricultural areas with high clay or sand content, a soil-specific calibration should be conducted to ensure accurate measurements in these soil types.
- Future work should develop equations to correct the errors caused by soil salinity, organic matter, and bulk density (ρb), which would further improve the accuracy of the soil moisture measurements.
- Integrating machine learning techniques with the sensor could potentially enhance irrigation management by predicting optimal schedules [26].

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