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Experimental Evaluation of Cable Length Effects on the Accuracy and Stability of Soil Moisture Sensor Measurements for ESP32-Based Monitoring Systems

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ABSTRACT

The use of soil moisture sensors in ESP32-based monitoring systems requires reliable measurement stability, particularly when sensors are installed far from the data acquisition unit. This study experimentally evaluates the effect of cable length on the characteristics and stability of soil moisture sensor measurements. Three sensor channels were tested using two cable configurations, namely the original cable and a 7-meter cable, under wet and dry conditions. The 12-bit ADC output data were evaluated using mean, standard deviation, coefficient of variation (CV), bias, mean absolute error (MAE), and root mean square error (RMSE). Under wet conditions, the 7-meter cable produced mean reading changes of +6.68% for ADC 1, −1.53% for ADC 2, and −0.71% for ADC 3. ADC 2 demonstrated the highest stability, with CV values of 0.16% and 0.78% for the original and 7-meter cables, respectively. Under dry conditions, all channels reached the maximum ADC value of 4095, indicating 12-bit ADC saturation. Overall, the ADC 2 configuration using the F2PH245082A sensor provided the most stable performance. These results confirm that cable length should be considered when designing ESP32-based analog sensor acquisition systems for reliable field monitoring applications.

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1. INTRODUCTION

Soil moisture monitoring is an important component in the development of precision agriculture, automated irrigation, and Internet of Things (IoT)-based agricultural systems. Information on soil moisture conditions serves as a basis for determining crop water requirements, optimizing irrigation schedules, and improving water-use efficiency[1][2][3]. In practical implementation, soil moisture sensors are commonly connected to microcontrollers or data acquisition systems, such as the ESP32, to acquire analog sensor signals, process the data, and transmit them to data storage devices or real-time monitoring platforms[4][5]. However, the accuracy of such systems is determined not only by sensor characteristics and analog-to-digital converter (ADC) resolution, but also by installation configurations, including the length of the cable connecting the sensor to the data acquisition unit.

This research investigates the signal degradation and impedance variations introduced by extended cable runs when interfacing resistivity and capacitive sensors with the ESP32's analog-to-digital converter[6][7]. As these sensors convert physical capacitance into voltage signals, long-distance cabling introduces parasitic resistance and electromagnetic interference that can significantly compromise the precision of the raw data [8]. Furthermore, these long-range deployments often necessitate a critical trade-off between the affordability of low-cost, capacitive-based sensing modules and the maintenance of signal integrity across distributed agricultural monitoring nodes[9,10] thereby highlighting the necessity of integrating robust signal conditioning techniques to maintain measurement accuracy in large-scale deployments[11]. To address these challenges, implementing localized processing architectures or

minimizing external circuitry requirements can effectively mitigate the polarization effects and noise that otherwise degrade data quality[12]. Specifically, the integration of voltage-based measurement strategies, such as AC impedance voltage division, may offer improved stability against the varying dielectric properties of diverse soil textures[13]. Moreover, adopting frequency-based measurement techniques within the 10–100 kHz range can enhance the consistency of soil volumetric water content readings by decoupling environmental noise from the capacitive response[14]. Such analytical improvements are essential for calibrating sensors across various soil compositions, ensuring that the sensor's output voltage maintains a reliable relationship with gravimetric water content. Consequently, characterizing the performance of these low-cost capacitive sensors across heterogeneous soil profiles remains a priority to validate the reliability of automated irrigation frameworks[15,16]. By evaluating the variability of sensor performance under field-calibrated conditions, researchers can establish robust models that effectively minimize measurement errors even when interfacing with budget-friendly hardware[17]. Moreover, future iterations must account for mechanical installation factors, as poor soil-sensor contact frequently induces measurement drift during the initial settling period[18]. Additionally, optimizing the depth of sensor placement is critical, as soil heterogeneity and water extraction patterns inherently influence the dielectric interactions that capacitive probes measure[19]. Given these environmental complexities, utilizing a higher density of low-cost sensors can help mitigate the risks posed by localized soil variability and representative site selection[20]. Furthermore, the inherent sensor-to-sensor variability observed in capacitive technology necessitates a rigorous two-step calibration procedure to ensure consistent performance across large-scale deployments[21,22]. Specifically, employing texture-specific linear calibration functions has been shown to reduce root mean square error by up to 70 percent, effectively addressing the performance discrepancies induced by varying soil mineralogy and organic matter content[23]. This optimization is particularly vital in high-organic soils, where low-frequency capacitive sensors often struggle to accurately distinguish between moisture levels and complex soil dielectric responses. Moreover, longitudinal data collection must maintain consistent measurement intervals to prevent temporal drift in recorded volumetric values, which often occurs when sensors are subjected to differing field-installation durations[24]. Finally, deploying these sensors alongside gravimetric sampling provides a necessary ground-truth benchmark to validate long-term stability and calibrate against site-specific environmental interference[25]. Future studies should prioritize the development of standardized, commercially viable mounting protocols to ensure that signal consistency is maintained across various real-world agricultural environments[26]. These operational frameworks must transition from experimental prototypes toward resilient, low-maintenance infrastructures, ensuring that the digital farming ecosystem evolves beyond a "set-and-forget" mentality[27].

2. METHOD

This study employs a comparative experimental method to evaluate the effect of cable length on the relative accuracy and stability of soil moisture sensor measurements connected to an ESP32-based data acquisition system. The primary variable investigated is the sensor cable configuration, consisting of the original sensor cable and a 7-meter extension cable. The experiments were conducted under two medium conditions, namely wet and dry conditions, using three sensor measurement channels designated as ADC 1, ADC 2, and ADC 3. Based on the experimental dataset, measurements using the original cable were collected on August 26, 2026, while measurements using the 7-meter cable were collected on August 27, 2026, with a recording interval of approximately one minute.

2.1. Equipment and Materials

The main equipment used in this study included an ESP32 as the data acquisition unit, three soil moisture sensors connected to the ADC channels, the original sensor cables, a 7-meter extension cable, a computer for data monitoring and storage, and soil as the testing medium. The system employed a 12-bit ADC**,** providing a digital measurement range of 0–4095. Under dry conditions, all sensor channels produced an ADC reading of 4095**,** corresponding to the maximum value of the 12-bit ADC. Therefore, this value was considered to represent the ADC saturation condition in the measurement system.

2.2. Research Variables

The independent variable in this study was the sensor cable length, consisting of two configurations: the original sensor cable and a 7-meter cable. The experimental conditions consisted of wet and dry soil media, while the dependent variable was the ADC output value of the sensor. The statistical parameters used to evaluate measurement performance included the mean, minimum, maximum, standard deviation, coefficient of variation (CV), bias, mean absolute error (MAE), and root mean square error (RMSE). To ensure valid and reproducible comparisons, subsequent experiments should maintain consistent experimental

conditions, including the sensor type, ESP32 ADC channel, power supply, sensor position and insertion depth in the soil, volume of the testing medium, and soil wetting procedure throughout all measurements.

2.3. Experimental System Configuration

The basic configuration of the experimental system is illustrated in Figure 1.

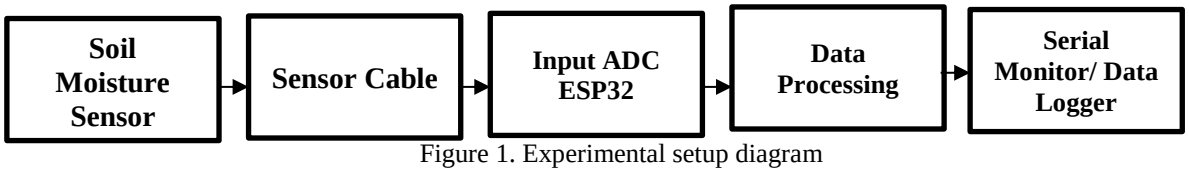


Figure 1. Experimental setup diagram

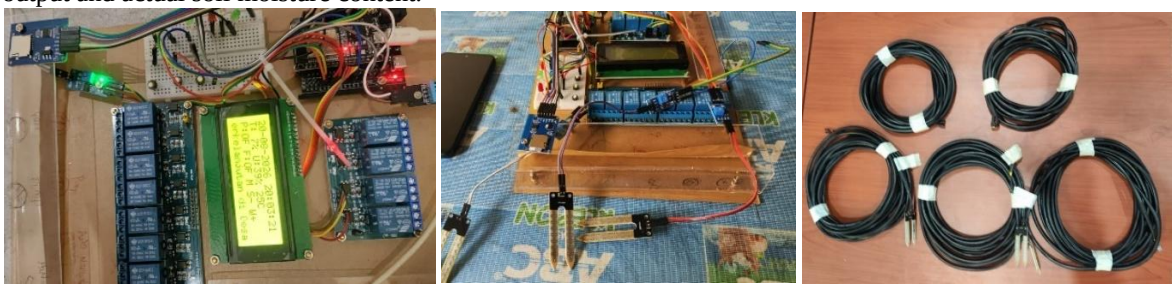
Figure 1 shows the experimental configuration used to evaluate the effect of cable length on soil moisture sensor measurements. In the first configuration, the sensors were connected to the ESP32 using their original cables. In the second configuration, the sensor cables were extended to obtain a total measurement cable length of 7 meters. The extension cable used was NYYHY 2 × 0.75 mm². To ensure a consistent comparison between the two configurations, the same ESP32 ADC input pin was maintained for each sensor throughout the experiments. This arrangement was intended to minimize measurement variations associated with differences among the ADC channel characteristics.

The detailed hardware configurations are presented in Figure 2. Figure 2(a) shows the ESP32 microcontroller used as the main data acquisition unit. Figure 2(b) presents the experimental setup using three soil moisture sensors connected through their original cables, while Figure 2(c) shows the corresponding configuration in which the sensor cables were extended to a total length of 7 meters using NYYHY 2 × 0.75 mm² cable. Except for the cable length, the sensor channels and measurement configuration were maintained consistently to enable a direct comparison of the sensor responses under the two experimental configurations.

Figure 2. Experimental hardware configuration: (a) ESP32 microcontroller used as the data acquisition unit, (b) three soil moisture sensors with the original cable configuration, and (c) soil moisture sensors with 7-meter NYYHY 2 × 0.75 mm² cable extensions.

2.4. System Preparation

Prior to the experiments, the ESP32 and soil moisture sensors were powered on and allowed to reach stable operating conditions. All cable connections were carefully inspected to ensure that there were no loose or improper connections that could affect the measurement results. The sensors were then inserted into the soil medium at the same position and depth for all experimental trials. To improve measurement repeatability, the sensor insertion depth should be standardized, for example, by placing a fixed reference mark on each sensor probe. The soil volume and testing container should also be maintained consistently throughout the experiments to minimize variations caused by changes in the testing medium. For future studies, additional parameters, particularly ambient temperature and gravimetric soil moisture content, should be recorded as supporting variables. Gravimetric measurements would provide an independent reference for evaluating sensor responses and developing a more comprehensive calibration relationship between ADC output and actual soil moisture content.



(a) (b) (c)

Figure 2. Experimental Configuration for Sensor Cable Testing

2.5. Testing Using the Original Cable

The first stage of the experiment was conducted using the original sensor cables. The soil medium was initially prepared under wet conditions. The three sensors were inserted into the testing medium, and the ADC values from ADC 1, ADC 2, and ADC 3 were recorded periodically. In this experimental dataset,

measurements under wet conditions using the original cables began at approximately 12:20 p.m. on August 26, 2026. Data were collected repeatedly at intervals of approximately one minute. After completing the wet-condition measurements, the sensors were tested under dry conditions. Under these conditions, all three ADC channels produced a value of 4095. This value was recorded as the maximum system response under dry conditions, corresponding to the full-scale limit of the 12-bit ADC.

2.6. Testing Using the 7-Meter Cable

The same experimental procedure was subsequently repeated using a 7-meter cable. The sensor type, ADC channels, power supply, and ESP32 program configuration were maintained unchanged to ensure consistency between the two experimental configurations. The soil medium was again prepared under wet conditions. Based on the experimental dataset, measurements using the 7-meter cable began at approximately 2:44 p.m. on August 27, 2026. The values of ADC 1, ADC 2, and ADC 3 were recorded at intervals of approximately one minute. After completing the wet-condition measurements, the sensors were tested under dry conditions. Under these conditions, all ADC channels again reached a value of 4095, indicating the full-scale response of the 12-bit ADC.

2.7. Statistical Data Analysis

Each group of experimental data was analyzed using descriptive statistical methods to evaluate the measurement characteristics and stability of the sensor outputs under different cable configurations. The statistical parameters included the mean, minimum and maximum values, standard deviation, coefficient of variation (CV), bias, mean absolute error (MAE), and root mean square error (RMSE).

The arithmetic mean of the ADC readings was calculated as:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \quad (1)$$

where: $\bar{x}$ represents the mean ADC value, n = is the number of samples, and x = represents the individual ADC reading. The standard deviation was calculated using:

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \quad (2)$$

The relative stability of the sensor measurements was evaluated using the coefficient of variation (CV):

$$CV = \frac{SD}{\bar{x}} \times 100\% \quad (3)$$

A lower CV value indicates lower variability in the ADC readings and, consequently, better measurement stability of the sensor.

2.8. Calculation of Cable Length Effects

The change in the mean ADC reading resulting from the use of the 7-meter cable was calculated relative to the original cable using the following equation:

$$\text{Bias}(\%) = \frac{\bar{x}_{7m} - \bar{x}_{ori}}{\bar{x}_{ori}} \times 100\% \quad (4)$$

where $\bar{x}_{7m}$ is the mean ADC reading obtained using the 7-meter cable, and $\bar{x}_{ori}$ is the mean ADC reading obtained using the original cable. A positive bias indicates an increase in the ADC reading after the use of the 7-meter cable, whereas a negative bias indicates a decrease in the ADC reading. Based on the experimental dataset, the changes in the mean ADC readings were approximately +6.68% for ADC 1, −1.53% for ADC 2, and −0.71% for ADC 3. Since the measurements using the original and 7-meter cables were obtained at different experimental times, these values are more appropriately interpreted as inter-configuration bias rather than absolute measurement errors relative to the actual soil moisture content.

2.9. Mean Absolute Error and Root Mean Square Error

The differences in ADC readings between the original cable and 7-meter cable configurations were evaluated using the Mean Absolute Error (MAE):

$$MAE = \frac{1}{n}\sum_{i=1}^{n} | x_{7m,i} - x_{ori,i} | \quad (5)$$

In addition to MAE, the Root Mean Square Error (RMSE) was calculated as:

$$MSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_{7m,i} - x_{ori,i}\right)^2 \quad)} \tag{6}$$

where $x_{7m,i}$ represents the i-th ADC reading obtained using the 7-meter cable, $x_{ori,i}$ represents the i-th ADC reading obtained using the original cable, and n is the number of paired observations. Lower MAE and RMSE values indicate smaller differences in ADC readings between the original and 7-meter cable configurations. However, the interpretation of MAE and RMSE requires paired measurements that experimentally represent comparable soil conditions. Therefore, in future experiments, the original and 7-meter cable configurations should be evaluated under identical soil moisture conditions and within closely spaced measurement intervals to minimize the influence of temporal variations in the testing medium.

2.10. Criteria for Selecting the Best Sensor

A sensor was considered more suitable for an ESP32-based soil moisture monitoring system when it simultaneously satisfied several performance criteria, including a low coefficient of variation (CV), a small change in the mean ADC value after extending the cable length to 7 meters, low Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) values, a clear ability to distinguish between wet and dry soil conditions, and low measurement fluctuations throughout the observation period. In addition, the sensor should maintain consistent measurement characteristics when operated with a longer cable. Based on these criteria, the sensor exhibiting the lowest overall CV, bias, MAE, and RMSE values, while maintaining clear discrimination between wet and dry conditions and stable measurements, was considered the most suitable sensor for implementation in the ESP32-based soil moisture monitoring system.

3. RESULTS AND DISCUSSION

3.1. Sensor Reading Characteristics under Wet and Dry Conditions

Based on the experimental results presented in Table 1, the three sensor channels exhibited clear differences between wet and dry medium conditions. Under wet conditions using the original cables, the mean values of ADC 1, ADC 2, and ADC 3 were 1961.93, 2706.90, and 2342.52, respectively. When the cable length was extended to 7 m, the corresponding mean values changed to 2092.90, 2665.48, and 2325.86, respectively. These results indicate that increasing the cable length produced different effects on each measurement channel. ADC 1 exhibited an increase in the mean value of 130.97 ADC counts, corresponding to 6.68%, whereas ADC 2 showed a decrease of 41.41 ADC counts or 1.53%, and ADC 3 showed a decrease of 16.66 ADC counts or 0.71%. Based solely on the changes in mean ADC values, ADC 3 exhibited the smallest relative deviation due to cable extension, whereas ADC 1 showed the largest change.

In contrast, under dry conditions, all sensor channels produced an ADC value of 4095 for both the original and 7 m cable configurations. Since 4095 represents the maximum digital output of a 12-bit ADC, these results indicate that the measurement system reached an ADC saturation condition. Therefore, identical readings of 4095 cannot be directly interpreted as evidence that cable length had no effect on sensor measurements under dry conditions. Under saturation, variations in the analog input voltage beyond the measurable range of the ADC cannot be distinguished from the digital output. Consequently, the effect of cable length can be evaluated more meaningfully using the measurements obtained under wet conditions, where the ADC outputs remained within the measurable range.

Table 1. Summary of Mean ADC Readings under Different Medium Conditions and Cable Lengths.

Condition	ADC 1	ADC 2	ADC 3
Wet – original cable	1961.93	2706.90	2342.52
Dry – original cable	4095.00	4095.00	4095.00
Wet – 7 m cable	2092.90	2665.48	2325.86
Dry – 7 m cable	4095.00	4095.00	4095.00
Change under wet conditions: original → 7 m	+6.68%	−1.53%	−0.71%

3.2. Stability Analysis Based on Standard Deviation and Coefficient of Variation

Table 2 shows differences in the dispersion of measurements among the three sensor channels. With the original cable, ADC 2 exhibited a standard deviation (SD) of only 4.37 and a coefficient of variation (CV) of

0.16%, which were substantially lower than those of ADC 1, with an SD of 64.98 and a CV of 3.31%, and ADC 3, with an SD of 142.54 and a CV of 6.08%. These results indicate that ADC 2 provided the most consistent measurements when using the original cable.After the cable length was extended to 7 m, the standard deviation of ADC 2 increased to 20.85, while its CV increased to 0.78%. Despite this increase in variability, the CV remained below 1%, indicating that ADC 2 maintained the highest relative measurement stability. For ADC 1, the SD increased from 64.98 to 90.27, while the CV increased from 3.31% to 4.31%. This result indicates that the use of the 7 m cable not only shifted the mean ADC 1 reading but also increased its measurement variability. A different characteristic was observed for ADC 3. Its standard deviation decreased from 142.54 to 54.68, while the CV decreased from 6.08% to 2.35%. Thus, the 7 m cable configuration for ADC 3 produced more concentrated measurements than the original cable configuration. However, this reduction in variability does not necessarily demonstrate that the 7 m cable improved sensor performance because the two measurements were obtained from different experimental datasets and testing conditions. Overall, based on the CV values, the stability ranking for the 7 m cable configuration was ADC 2 > ADC 3 > ADC 1. The CV of 0.78% for ADC 2 represents the lowest relative variability among the three channels.

Table 2. Standard Deviation and Coefficient of Variation of Sensor Readings under Wet Conditions

Sensor	Wet – Original Cable: SD	CV	Wet – 7 m Cable: SD	CV
ADC 1	64.98	3.31%	90.27	4.31%
ADC 2	4.37	0.16%	20.85	0.78%
ADC 3	142.54	6.08%	54.68	2.35%

3.3. Bias Analysis Due to Changes in Cable Length

The results presented in Table 3 demonstrate that the effect of cable length was reflected not only in measurement variability but also in shifts in the mean ADC values. The bias was calculated as the difference between the mean ADC reading obtained using the 7 m cable and that obtained using the original cable:

$$Bias = x_{7m} - x_{original} \quad (7)$$

ADC 1 exhibited a positive bias of +130.97 ADC counts, indicating that its mean output increased after the 7 m cable was used. In contrast, ADC 2 and ADC 3 exhibited negative biases of −41.41 ADC counts and −16.66 ADC counts, respectively. When normalized relative to the mean values obtained using the original cable, ADC 1 exhibited the largest relative bias of +6.68%, whereas ADC 2 and ADC 3 exhibited relative biases of −1.53% and −0.71%, respectively. From the perspective of the shift in the mean ADC value, ADC 3 demonstrated the lowest sensitivity to changes in cable configuration. However, a small mean bias alone is insufficient to identify the best-performing sensor because a sensor with a small mean bias may still exhibit substantial variation among individual measurements. Therefore, the bias analysis should be considered together with other statistical indicators, including SD, CV, MAE, and RMSE, to provide a more comprehensive assessment of measurement performance.

3.4. MAE and RMSE Analysis

Based on the statistical results presented in Table 3 and the sample-wise differences shown in Table 4, ADC 1 produced an MAE of 139.10 ADC counts and an RMSE of 155.06 ADC counts. ADC 2 exhibited substantially lower values, with an MAE of 41.41 ADC counts and an RMSE of 45.88 ADC counts. In contrast, ADC 3 produced the highest MAE of 146.66 ADC counts and an RMSE of 174.09 ADC counts. The RMSE was consistently equal to or greater than the MAE because the RMSE assigns greater weight to large-magnitude deviations through the squaring operation. This behavior was particularly evident for ADC 3. Although its mean bias was only −16.66 ADC counts, corresponding to −0.71%, its MAE and RMSE were the highest among the three channels. This result indicates that a small mean bias does not necessarily correspond to high measurement stability.

This phenomenon can be explained by the sample-wise differences presented in Table 4. For ADC 3, the differences between the 7 m and original cable configurations varied considerably in both magnitude and direction. For example, a positive difference of +408 ADC counts was observed for one sample, whereas another sample exhibited a difference of −226 ADC counts. Because positive and negative deviations can partially cancel each other when calculating the mean bias, a relatively small bias may be obtained even when individual measurement differences remain large. In contrast, MAE and RMSE are insensitive to this cancellation because they are based on absolute and squared differences, respectively.

Table 3. Statistical Analysis of the Effect of Cable Length on Sensor Readings under Wet Conditions

Sensor /Channel	Mean Original	Mean 7 m	ADC Bias	Bias (%)	Index-wise MAE	Index-wise RMSE	CV Original (%)	CV 7 m (%)	Welch's *p*-value
ADC 1	1961.93	2092.90	+130.97	+6.68	139.10	155.06	3.31	4.31	6.028×10^{-8}
ADC 2	2706.90	2665.48	−41.41	−1.53	41.41	45.88	0.16	0.78	1.299×10^{-11}
ADC 3	2342.52	2325.86	−16.66	−0.71	146.66	174.09	6.08	2.35	5.605×10^{-1}

Therefore, the evaluation of cable-length effects should not rely solely on mean bias. A more comprehensive assessment requires the simultaneous consideration of bias, MAE, RMSE, standard deviation, and coefficient of variation to characterize both systematic shifts and measurement variability.

3.5. Analysis of Individual Difference Patterns

The data presented in Table 4 provide a more detailed description of the distribution of differences between ADC readings obtained using the 7 m cable and those obtained using the original cable. For ADC 1, most of the differences were positive, with several relatively large deviations, including +238, +212, and +333 ADC counts. This predominantly positive pattern is consistent with the mean bias of +130.97 ADC counts, indicating a tendency for ADC 1 readings to shift toward higher values when the 7 m cable was used.

Table 4. Differences in ADC Readings between the Original Cable and the 7 m Cable under Wet Conditions.

Diff ADC1	Diff ADC2	Diff ADC3	Abs ADC1	Abs ADC2	Abs ADC3	Sq ADC1	Sq ADC2	Sq ADC3
-74	-47	311	74	47	311	5,476	2,209	96,721
238	-42	408	238	42	408	56,644	1,764	166,464
138	-62	243	138	62	243	19,044	3,844	59,049
84	-65	254	84	65	254	7,056	4,225	64,516
62	-65	100	62	65	100	3,844	4,225	10,000
127	-60	102	127	60	102	16,129	3,600	10,404
184	-71	65	184	71	65	33,856	5,041	4,225
172	-77	64	172	77	64	29,584	5,929	4,096
181	-71	-13	181	71	13	32,761	5,041	169
212	-56	-39	212	56	39	44,944	3,136	1,521
333	-52	-116	333	52	116	110,889	2,704	13,456
-40	-36	-10	40	36	10	1,600	1,296	100
-4	-39	-64	4	39	64	16	1,521	4,096
15	-38	-91	15	38	91	225	1,444	8,281
97	-33	-104	97	33	104	9,409	1,089	10,816
125	-11	-147	125	11	147	15,625	121	21,609
120	-33	-120	120	33	120	14,400	1,089	14,400
134	-21	-97	134	21	97	17,956	441	9,409
141	-22	-127	141	22	127	19,881	484	16,129
150	-29	-181	150	29	181	22,500	841	32,761
143	-30	-202	143	30	202	20,449	900	40,804
171	-27	-195	171	27	195	29,241	729	38,025
187	-25	-198	187	25	198	34,969	625	39,204
178	-38	-226	178	38	226	31,684	1,444	51,076
196	-20	-214	196	20	214	38,416	400	45,796
172	-24	-224	172	24	224	29,584	576	50,176
128	-6	235	128	6	235	16,384	36	55,225
48	-26	102	48	26	102	2,304	676	10,404

ADC 2 exhibited a different pattern. All differences in the dataset were negative, ranging approximately from −6 to −77 ADC counts. This consistent direction indicates a systematic shift toward lower ADC readings after the cable length was increased to 7 m. Despite this systematic bias, the magnitude of the

differences was relatively small compared with those observed for ADC 1 and ADC 3. This characteristic explains why ADC 2 produced the lowest MAE and RMSE values among the three measurement channels.

ADC 3 exhibited a considerably more complex difference pattern. During the initial measurements, relatively large positive differences of +311, +408, +243, and +254 ADC counts were observed. The differences subsequently shifted toward negative values, reaching as low as −226 ADC counts, before becoming positive again for several of the final samples. This alternating pattern indicates greater inter-configuration variability and contributes to the relatively high RMSE of 174.09 ADC counts. Thus, although ADC 3 exhibited the smallest mean relative bias, its sample-wise differences reveal that it was less consistent than ADC 2.

3.6. Statistical Analysis Using Welch's t-Test

Welch's t-test was employed to determine whether the differences in mean ADC readings between the original and 7 m cable configurations were statistically significant. ADC 1 yielded a p-value of 6.028×10^{-8}, whereas ADC 2 yielded a p-value of 1.299×10^{-11}. Both values were substantially lower than the significance level of \(\alpha = 0.05\). Therefore, the differences in mean ADC readings between the original and 7 m cable configurations were statistically significant for ADC 1 and ADC 2. The statistical results for the three channels are reported in Table 3.

In contrast, ADC 3 yielded a p-value of 0.5605, which was greater than the significance level of 0.05. Therefore, there was insufficient statistical evidence to conclude that the mean ADC 3 readings differed significantly between the two cable configurations. This finding is particularly noteworthy because ADC 3 exhibited relatively high MAE and RMSE values despite the absence of a statistically significant difference in its mean readings. This result demonstrates that mean-difference testing and deviation-based metrics evaluate different aspects of measurement behavior. Welch's t-test assesses differences between the central tendencies of two distributions, whereas MAE and RMSE quantify the magnitude of sample-wise deviations without allowing positive and negative differences to cancel each other.

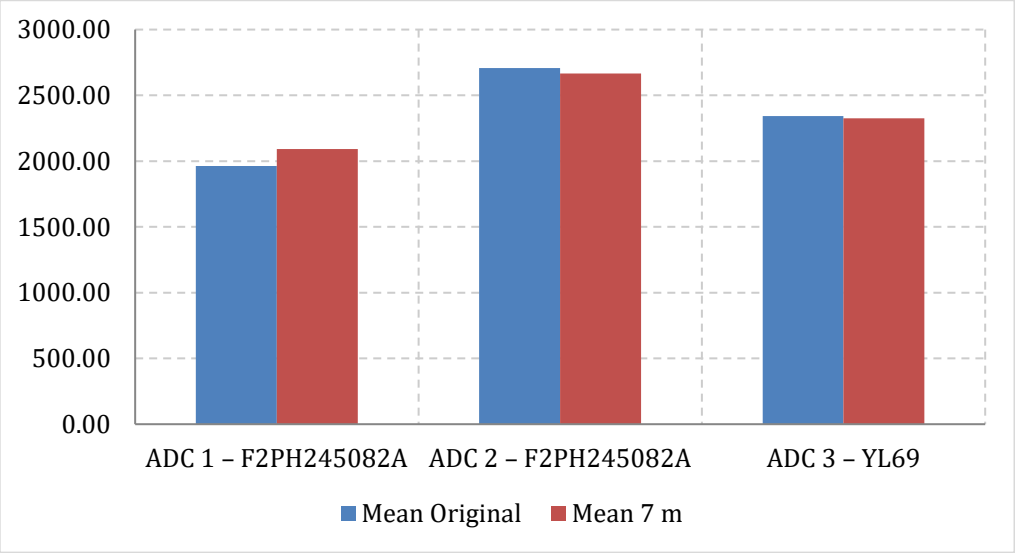


Figure 2. Experimental configuration for evaluating the effect of cable length on the readings of ESP32-based soil moisture sensors.

3.7. Sensor Evaluation for ESP32-Based Monitoring Systems

When the evaluation is based solely on relative bias, ADC 3 appears to provide the best performance, with a mean change of only −0.71%. However, ADC 3 exhibited a CV of 6.08% with the original cable, an MAE of 146.66 ADC counts, and an RMSE of 174.09 ADC counts. Therefore, its relatively small bias was not accompanied by comparable measurement consistency. ADC 1 exhibited less favorable performance when the cable length was increased, with a relative bias of +6.68%, while its CV increased from 3.31% to 4.31%. These results indicate that cable extension affected both the mean ADC reading and its measurement variability.

Among the three channels, ADC 2 demonstrated the best overall performance trade-off. Although its mean reading shifted by −1.53%, and the difference between the two cable configurations was statistically significant, ADC 2 exhibited the lowest CV values of 0.16% and 0.78% for the original and 7 m cables, respectively. It also produced the lowest MAE and RMSE values, at 41.41 and 45.88 ADC counts,

respectively. Therefore, ADC 2 provided the most consistent measurements, with the effect of the 7 m cable remaining relatively limited compared with those observed for ADC 1 and ADC 3.

4. CONCLUSION

Based on the experimental results and statistical analysis, cable length was found to influence the measurement characteristics of soil moisture sensors in the ESP32-based monitoring system. Under wet conditions, the use of a 7 m cable resulted in mean ADC reading changes of +6.68% for ADC 1, −1.53% for ADC 2, and −0.71% for ADC 3 compared with the original cable configuration. ADC 2 demonstrated the highest measurement stability, with coefficient of variation values of 0.16% for the original cable and 0.78% for the 7 m cable, while maintaining a relatively small shift in the mean reading. In contrast, ADC 1 exhibited the greatest sensitivity to cable extension. Under dry conditions, all channels reached an ADC value of 4095, indicating saturation of the 12-bit ADC. Considering the combined performance indicators, including mean values, variability, bias, MAE, and RMSE, the ADC 2/F2PH245082A configuration demonstrated the most stable performance and the greatest potential for ESP32-based soil moisture monitoring systems. Nevertheless, calibration at multiple soil moisture levels is required to determine the absolute accuracy, linearity, sensitivity, and reliability of the sensor for practical field applications.

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