Indonesian Journal of Electrical Engineering and Computer Science
Vol. 41, No. 2, February 2026, pp. 470~477
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v41.i2.pp470-477

Enhanced soil moisture sensing using graphene-coated copper electrodes

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Article Info

Article history:

Received Jun 26, 2025
Revised Dec 31, 2025
Accepted Jan 11, 2026

Keywords:

Conductivity
Drop casting
Graphene
Precision agriculture
Soil moisture

ABSTRACT

Soil moisture monitoring is essential for precision agriculture to optimize irrigation and increase crop productivity. Traditional conductivity-based sensors often face limitations such as low sensitivity, slow response, and measurement instability. This study presents a simple and effective enhancement method by applying a graphene coating on copper electrodes using the drop casting technique. Experimental evaluations were conducted on natural soil samples at varying moisture levels. The graphene-coated sensor exhibited a significantly higher sensitivity of 23.0 Ω/% compared to 12.0 Ω/% for the uncoated sensor, a faster response time of approximately 5 seconds, and improved measurement consistency with a reduced standard deviation of ±15 Ω. Graphene's superior electrical conductivity and strong water affinity are key factors contributing to this performance improvement. These findings indicate that graphene-coated sensors offer a promising solution for reliable, cost-effective soil moisture monitoring in smart farming systems.

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1. INTRODUCTION

Precision agriculture represents a modern farming strategy that aims to enhance productivity by efficiently managing resources, increasing crop output, and supporting ecological balance [1], [2]. A key factor in achieving these outcomes is the measurement of soil moisture, as it plays a vital role in controlling irrigation, maintaining crop vitality, and ensuring effective nutrient delivery. Soil moisture is a critical parameter in agriculture, as it directly impacts plant health, irrigation efficiency, and overall crop yield [3], [4]. Effective soil moisture management supports precision agriculture by enabling farmers to conserve water, prevent over-irrigation, and ensure optimal plant growth [5], [6]. Reliable and accurate moisture sensing technology is therefore indispensable in modern smart farming systems.

Among various sensing technologies, conductivity-based soil moisture sensors are widely adopted due to their simplicity, affordability, and rapid response [7], [8]. These sensors typically measure the resistance between two metal electrodes inserted into the soil. As the soil moisture increases, the number of free ions increases, resulting in a reduction in measured resistance [9]–[11]. However, traditional conductivity sensors often suffer from limited sensitivity and high variability, especially under fluctuating soil conditions such as changes in pH, temperature, and ion concentration [12]–[15].

Copper is widely utilized as an electrode material due to its superior electrical conductivity and widespread availability [16], [17]. However, it is prone to corrosion and oxidation, particularly in moist and chemically reactive soil environments. Such deterioration can reduce the sensor's lifespan and lead to inaccurate measurements [18].

To address these challenges, advanced materials like graphene have been introduced to improve sensor performance. Graphene is known for its exceptional electrical conductivity, large specific surface area, and hydrophilic nature, which enhance its interaction with water molecules [19]–[21]. Recent studies have demonstrated that graphene-modified sensors can significantly increase sensitivity and stability, providing more reliable data in complex environments. For instance, Palaparthy *et al.* [22] developed a graphene oxide-based capacitive soil moisture microsensor that exhibited a rapid response time of 100–120 seconds and a sensitivity increase of over 340% across a soil moisture range of 1% to 55%, highlighting its robustness in variable soil conditions. Similarly, Siddiqui *et al.* [23] designed a graphene oxide sensor array capable of detecting deep soil moisture variations with a signal response exceeding 500%, while maintaining a low deviation of ±2.4% when benchmarked against the oven-dry method. These findings confirm that graphene integration not only enhances electrical performance but also ensures greater durability and measurement precision under fluctuating environmental conditions.

This study focuses on enhancing the sensitivity of copper-based conductivity sensors through graphene coating applied via a drop casting method. The objective is to quantitatively assess the impact of the graphene layer on sensor performance under varying soil moisture conditions. The work offers a practical approach for sensor improvement using simple fabrication techniques and provides experimental validation of the performance benefits in a natural soil setting.

Although previous studies have explored graphene-based sensing materials, most implementations rely on microfabricated structures or capacitive mechanisms with relatively complex fabrication [22], [23]. However, the application of graphene using a simple drop-casting technique on copper electrodes for low-cost conductivity-based soil moisture sensing has not been thoroughly investigated. This study contributes by providing a practical, economical enhancement method and quantitatively demonstrating improvements in sensitivity, response time, and signal stability under natural soil conditions.

2. PROPOSED METHOD

This study proposes an enhancement approach for a conductivity-based soil moisture sensor by modifying conventional copper electrodes using a graphene thin film deposited through a drop-casting technique. The method aims to improve sensitivity, response speed, and signal stability while maintaining low fabrication cost and simplicity.

2.1. Concept overview

Copper electrodes are commonly used in resistive soil moisture sensors due to their high conductivity and ease of fabrication. However, copper suffers from oxidation and surface degradation under moist soil conditions, leading to inconsistent readings and reduced sensitivity. Graphene is introduced as a surface-modification material because of its high electrical conductivity and favorable electrochemical properties [24], as well as its strong interaction with water molecules that enhances surface adsorption [19]. Graphene oxide (GO) and reduced graphene oxide (rGO) additionally present oxygen-containing functional groups that increase hydrophilicity and provide adsorption sites for water and ionic species. When applied onto copper substrates, graphene layers have been shown to inhibit corrosion and improve interfacial stability, which helps reduce fluctuations in contact resistance [25], [26]. Moreover, graphene-modified electrodes typically exhibit increased effective active area and enhanced charge-transfer kinetics, resulting in more uniform current distribution and improved sensor responsiveness [27].

2.2. Electrode modification procedure

The electrode modification procedure consists of two main stages. First, the copper sensing pads are cleaned using ethanol and fine abrasive material to remove surface oxidation and contaminants. This preparation step is essential to ensure good coating adhesion and uniform graphene deposition. Second, the graphene coating is applied through a drop-casting technique. A controlled amount of graphene suspension is dispensed onto the electrode surface using a micropipette and allowed to spread uniformly before drying at room temperature. This process forms a thin and continuous graphene layer over the copper surface. The drop-casting method is selected because it is simple, low-cost, and does not require specialized fabrication equipment, making it suitable for scalable surface modification and practical sensor enhancement.

2.3. Operating principle

The proposed sensor operates on the principle that soil electrical conductivity increases with moisture content due to higher ionic mobility and the formation of continuous water pathways. When a low-frequency AC excitation signal is applied across the electrodes, the resulting conductance depends on ion concentration in the soil water, water-mediated charge transfer at the electrode interface, and the effective surface area of the conductive layer. The graphene-oxide coating is expected to reduce interfacial impedance and enhance electron transfer, thereby producing a steeper conductance change as moisture varies. Measurements are acquired using a microcontroller-based readout circuit, which records resistance values and computes moisture levels based on calibrated relationships.

2.4. Expected performance outcomes

Based on the surface modification and material properties, the proposed method is expected to provide higher sensitivity due to improved interfacial conductivity, faster response time from rapid moisture–surface interaction, better signal stability as oxidation effects are minimized, and improved repeatability due to uniform graphene coating. These outcomes are validated experimentally, and findings are compared against existing low-cost soil moisture sensing technologies.

3. METHOD

3.1. Sensor fabrication

The result of the conductivity sensor design is shown in Figure 1. The sensor has a length of 5 cm, a width of 1 cm, and a thickness of 1 mm. It is constructed from several layers arranged in a composite–copper–pertinak–copper–composite structure. The outermost layers on both sides are composite materials with a thickness of 1 mm each. These composite layers are layered over a 1 mm thick copper layer. Between the two copper layers, there is a pertinak layer, which serves as an insulating board, with a thickness of 1 mm. The design is symmetrical, providing both mechanical stability and optimal conductivity. The sensor is also equipped with a pin socket, which facilitates electrical connections and integration into the measurement system.

The graphene coating is then applied to enhance the electrochemical, mechanical, or electronic properties of the pin surface, making it more suitable for sensor applications. The drop casting method involves placing a small droplet of graphene suspension onto the surface of the socket pin and allowing it to dry, resulting in a uniform and thin graphene layer. This technique is simple, cost-effective, and suitable for creating localized coatings on metallic surfaces [28], [29].

In Figure 2, the graphene-coated socket pin is immersed in an aqueous solution, indicating its use in electrochemical testing or sensing applications. The presence of graphene improves the electrode's sensitivity, conductivity, and stability in liquid environments. This modification demonstrates a practical approach to integrating advanced nanomaterials like graphene into conventional electrical components for enhanced performance in sensing and detection systems.

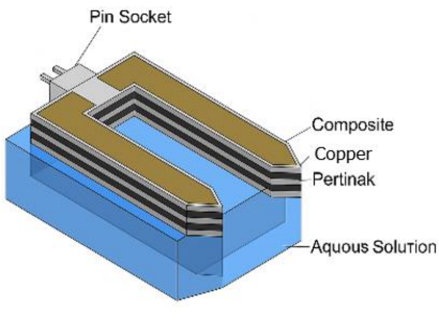

Figure 1. The conductivity sensor design

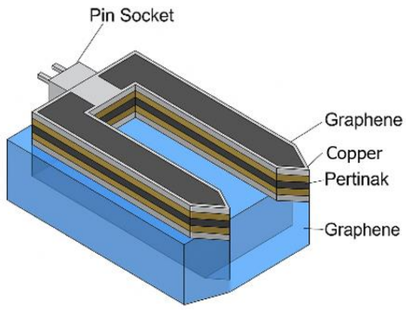

Figure 2. Sensor coated with thin graphene layer

3.2. Soil preparation and moisture conditioning

The experiments as shown in Figure 3 were conducted using natural soil samples with carefully controlled moisture content, which were categorized into four distinct levels to observe the sensor's performance across a range of soil conditions. The moisture levels were divided as follows:

– Very dry soil (5–10% moisture), where the soil appeared loose and crumbly with minimal water content.
– Dry soil (10–20% moisture), which still retained low levels of moisture but exhibited slightly cohesive properties.
– Moist soil (20–30% moisture), characterized by noticeable dampness and increased conductivity due to higher water presence.

– Saturated soil (>40% moisture), where the soil was visibly wet and reached near-maximum water absorption capacity.

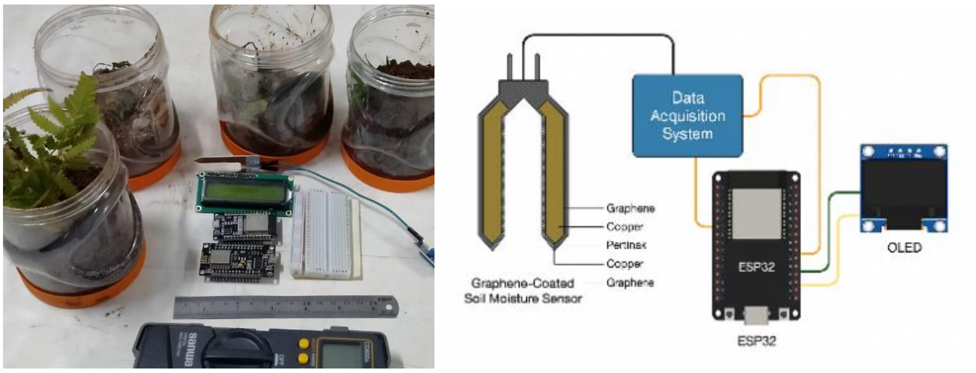

Figure 3. Soil samples with varying moisture levels and sensor wiring schematic

Each of these soil samples was systematically tested using both the graphene-coated sensor and the uncoated sensor to compare their sensitivity and electrical conductivity responses under different moisture conditions. This comparative approach aimed to evaluate the enhancement effect of the graphene layer on the sensor's performance across varying levels of soil moisture.

3.3. Measurement procedure

The resistance values of the sensors were recorded using a high-precision digital multimeter to ensure accurate and reliable measurements. Prior to each measurement, the sensors were carefully calibrated and connected to the soil samples under controlled laboratory conditions. To guarantee the repeatability and consistency of the data, each test condition was performed three times, and the average of these readings was used for analysis.

The following key parameters were evaluated to characterize the sensor’s performance:

a) Sensitivity (S): sensitivity was defined as the ratio of the change in electrical resistance to the corresponding change in soil moisture content. Mathematically, it can be calculated using (1), where ΔR represents the change in resistance in ohms (Ω), and ΔM denotes the change in soil moisture percentage (%). A higher sensitivity value indicates a more responsive sensor capable of detecting small variations in moisture content.

$$S = \frac{\Delta R}{\Delta M} \quad (1)$$

b) Response time (T_p): response time was determined as the time interval required for the sensor’s resistance value to reach 90% of its final steady-state value after a sudden change in soil moisture. This parameter reflects how quickly the sensor can respond to changes in environmental conditions, which is critical for real-time monitoring applications.

c) Signal consistency (σ): signal consistency was assessed by calculating the standard deviation of repeated resistance measurements at each moisture level. This statistical parameter indicates the precision and stability of the sensor readings, with lower values representing more consistent and reliable measurements.

For each moisture level, the resistance or conductivity reading was recorded three times to evaluate measurement stability and repeatability. The mean and standard deviation were computed to quantify noise levels and performance differences between the uncoated and graphene-coated sensors. The collected data were then used to analyze sensitivity trends, linearity, and overall performance improvement.

4. RESULTS AND DISCUSSION

4.1. Resistance vs soil moisture level

The first experiment was conducted to compare the resistance of soil moisture sensors with and without graphene coating under various soil moisture conditions. Two sensors were prepared: one sensor was left uncoated, while the other was modified by adding a graphene layer to its surface. Measurements were then performed by placing both sensors in soil samples with different moisture levels. The resistance values were recorded and analyzed to determine the effect of the graphene coating on sensor performance. The results show that the modified sensor consistently exhibited lower resistance than the uncoated sensor across all soil moisture conditions, indicating its higher sensitivity and improved conductive properties in response to soil water content, as presented in Table 1 and Figure 4.

Figure 4 demonstrates that the graphene-coated sensor consistently exhibits lower resistance at all moisture levels. The slope of the graphene-coated sensor is steeper, indicating improved sensitivity. The resistance decreased with increasing soil moisture for both sensor types, but the graphene-coated sensor showed a steeper slope, reflecting its higher sensitivity in response to soil moisture variations. This suggests that the graphene-coated sensor is more responsive and reliable for soil moisture monitoring applications.

Table 1. Resistance readings of uncoated and graphene-coated sensors at varying soil moisture levels

Soil moisture (%)	Resistance (Ω)	
	Uncoated	Graphene-coated
5-10	1,100	850
10-20	900	610
20-30	950	520
30-40	840	410

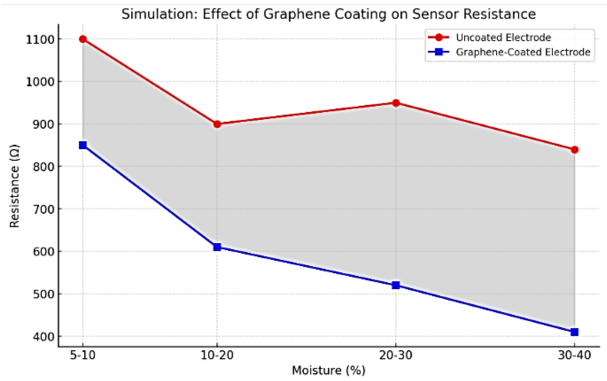

Figure 4. Comparison of resistance vs. moisture levels for uncoated and graphene-coated sensors

4.2. Performance comparison

The second experiment was conducted to compare the performance of soil moisture sensors with and without graphene coating in terms of sensitivity, response speed, and consistency of the reading results. In this test, two sensors were evaluated under the same soil moisture conditions: one sensor was left uncoated, while the other was modified by adding a graphene layer to its surface.

Table 2 shows the comparative performance between the uncoated sensor and the graphene-coated sensor under the same soil moisture variations. The table summarizes the measured resistance values, corresponding moisture levels, and the calculated sensitivity for both configurations. As shown in the table, the graphene-coated electrode consistently exhibits lower resistance at identical moisture levels, indicating improved charge transport and enhanced interaction with the surrounding soil medium. Furthermore, the sensitivity increases from 12.0 Ω/% for the uncoated electrode to 23.0 Ω/% with graphene modification, demonstrating that the coating substantially amplifies the sensor's responsiveness to moisture changes. This comparison highlights the performance improvement gained through surface modification and validates the effectiveness of the graphene layer in stabilizing the soil–electrode interface. Figure 5 clearly shows the performance improvements achieved with graphene coating: higher sensitivity, faster response, and greater measurement stability.

Table 2. Summary of sensor performance parameters

Parameter	Uncoated sensor	Graphene-coated sensor
Sensitivity	12.0 Ω/%	23.0 Ω/%
Response time	~12 sec	~5 sec
Standard deviation	±30 Ω	±15 Ω

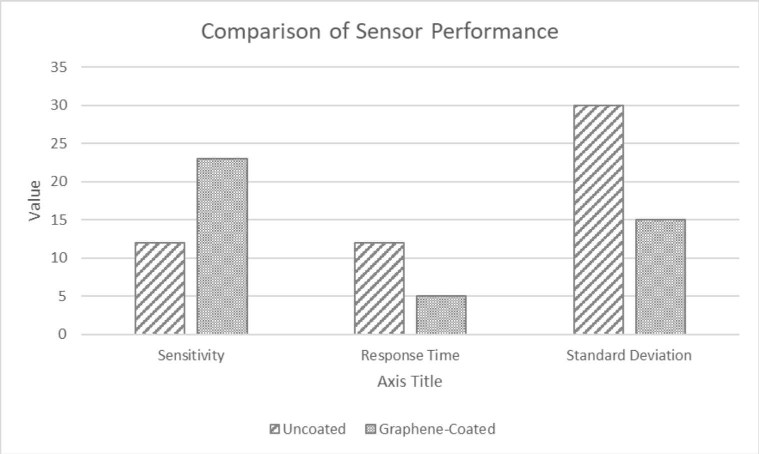

Figure 5. Bar chart comparing sensitivity, response time, and standard deviation between uncoated and graphene-coated sensors

4.3. Qualitative mechanism of improvement

The observed behavior aligns with the intrinsic material properties of graphene. Its high electrical conductivity facilitates more efficient charge transfer, while its hydrophilic functional groups promote rapid adsorption of water molecules and ions. The large active surface area improves contact uniformity, helping distribute current more evenly across the electrode surface. As a result, the graphene-coated electrode exhibits enhanced responsiveness and reduced drift. This qualitative explanation replaces the earlier simulation (COMSOL) approach to ensure that all results presented in the manuscript are fully reproducible based solely on experimental observations. Numerical modeling is left for future work.

4.4. Benchmarking against literature and commercial sensors

To contextualize the sensor performance, the results were compared with previously reported low-cost resistive probes and common commercial soil moisture technologies. Standard resistive probes typically exhibit low sensitivity (5–15 Ω/%) and are prone to corrosion and drift [19]. Gypsum blocks, while inexpensive, require long equilibration times and are unsuitable for real-time systems [20]. Capacitive sensors such as the EC-5 provide higher accuracy but rely on more complex fabrication and higher production costs [29]. The graphene-coated sensor in this study offers performance that surpasses typical low-cost resistive sensors while maintaining a simple and inexpensive fabrication process, making it a promising middle-ground solution for precision agriculture applications.

5. CONCLUSION

This study demonstrated that applying a graphene coating to copper-based conductivity soil moisture sensors significantly enhances measurement performance. The modified electrodes exhibited higher sensitivity, faster response, and improved stability compared to uncoated probes. These improvements are consistent with previously reported advantages of graphene-based interfaces and confirm its suitability for low-cost soil sensing applications. The proposed sensor also showed competitive behavior relative to commonly referenced low-cost commercial probes, while maintaining a simpler fabrication process. Future work may include validating long-term durability under varying soil conditions and extending benchmarking to additional commercial sensors. Overall, the graphene-coated electrode approach provides a practical enhancement path for improving the accuracy and robustness of resistive soil moisture sensors in precision agriculture.

ACKNOWLEDGMENTS

The authors would like to thank Politeknik Negeri Jakarta (PNJ) for supporting this research.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Nuralam	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓		✓
Rizdam Firly Muzakki				✓	✓	✓	✓	✓		✓			✓	
Sri Lestari Kusumastuti				✓	✓	✓							✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

This research does not involve human participants; therefore, informed consent was not required.

ETHICAL APPROVAL

The research doesn't involve humans or animal as participants; ethical approval was not necessary.

DATA AVAILABILITY

Derived data supporting the findings of this study are available from the first author [Nuralam] on request.

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