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Development and Performance Testing of a PANI–GO Soil Conductivity Sensor

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ABSTRACT

Smart agriculture systems require soil sensors capable of monitoring environmental conditions in real-time and with high accuracy. This research presents the design and fabrication of a soil conductivity sensor prototype using a composite material of Polyaniline (PANI) and Graphene Oxide (GO). The prototype is designed with a two-electrode structure based on copper layers, where the active PANI–GO layer functions as a conductive path that responds to soil moisture and ion levels. The PANI–GO composite was synthesized through a polymerization method and then applied to copper-based electrodes. Test results showed detectable changes in resistance according to variations in soil moisture content, where resistance values decreased as the soil became moister and more fertile. Moisture levels were adjusted to 10%, 20%, 30%, and 40% for two soil types: fertile and infertile. These results indicate the potential of the composite material as a simple soil sensor that can be further developed for Internet of Things (IoT) applications in agriculture. This study serves as a foundational step in the development of low-cost, flexible, and easily integrated conductive soil sensors.

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1. INTRODUCTION

Soil moisture is one of the most important parameters in agricultural cultivation, as it directly affects water availability for plants and the efficiency of nutrient uptake by roots. In conventional agricultural systems, soil moisture monitoring is often still performed manually or based on farmers' intuition, which tends to be less accurate and inefficient in the long term. To address this challenge, the concept of precision agriculture has been widely adopted, which is a technology-based approach to optimally manage land and crops through real-time data collection [1], [2]. One crucial element in this system is the availability of sensors capable of providing fast and accurate soil moisture information, with durable sensor construction materials.

The use of conductive material-based sensors is one of the promising approaches for soil moisture measurement. Materials such as Polyaniline (PANI) and Graphene Oxide (GO) are known for their high sensitivity to humidity due to their ability to conduct ions through resistance change mechanisms. Sensors based on these materials operate by detecting changes in electrical conductivity in the active layer when variations in soil moisture occur. PANI is known as a stable conductive polymer, while GO has a high surface area and hydrophilic functional groups that support interaction with water molecules [3]. The combination of both materials in composite form has been widely studied as a potential humidity sensor with good performance.

However, most previous studies have been limited to laboratory testing under homogeneous conditions or using only one type of soil as the testing medium. In fact, soil physical and chemical characteristics, such as texture, ion content, and porosity, can significantly affect sensor response [4]. Fertile soil, for example, generally contains higher mineral and organic matter content and has better water retention capacity compared to infertile soil [5]. Therefore, preliminary evaluation of sensor response in different soil types is necessary to provide a more representative overview of the sensor’s potential application in diverse agricultural environments.

Research on PANI-based humidity sensors shows that this polymer is capable of producing fast responses to humidity changes with high sensitivity and relatively simple fabrication processes [6]. The addition of nanomaterials such as graphene or GO has been reported to improve sensor performance, especially in terms of stability, flexibility, and conductivity [7]. In this context, this study focuses on controlled laboratory testing as an initial step to evaluate sensor characteristics before further validation under field conditions.

Fertile soil tends to have higher ion exchange capacity and organic matter content compared to infertile soil, which may influence sensor response to moisture. However, studies that explicitly compare the performance of PANI–GO-based conductivity sensors in two soil types with different fertility levels are still limited. This represents an important research gap to be addressed so that the sensor can be reliably used under various agricultural land conditions. Experimental testing of moisture variations in fertile and infertile soils can provide a more realistic picture of sensor performance in the field [8].

This study aims to develop a PANI–GO composite-based sensor to improve soil moisture detection capability. The sensor is tested under two different soil conditions: fertile and infertile soils. The main focus of testing is to evaluate changes in sensor resistance in response to variations in water content in each soil type, as well as to observe the stability of the generated signal. It is expected that the results of this study will serve as a foundation for the development of soil sensors that are more adaptive to real environmental conditions and support the implementation of intelligent and precise soil moisture monitoring systems.

2. METHOD

2.1. PANI–GO Semiconductor Material-Based Conductivity Sensor

A conductivity sensor based on semiconductor materials such as polyaniline (PANI) and graphene oxide (GO) operates by detecting changes in electrical resistance in response to environmental conditions, such as humidity. PANI, as a conductive polymer, possesses a structure that enables charge delocalization along its conjugated chains, and its conductivity can increase through interaction with water molecules [9]. On the other hand, GO contains hydrophilic functional groups such as hydroxyl, epoxy, and carboxyl groups, which facilitate the absorption of water and ions [10]. When water is absorbed by the PANI–GO composite material, the ions present in the water enhance charge mobility, thereby reducing the resistance between the electrodes. The combination of these two materials forms a conductive network that is responsive to moisture variations, offering improved sensitivity and signal stability compared to single-material systems [11].

2.2. Correlation Between Soil Moisture and Electrical Resistance

Soil moisture directly affects electrical resistance because water acts as a medium for ion conduction. At low moisture levels, the amount of water within soil pores is minimal, resulting in high resistance between soil particles or between electrodes. Conversely, as moisture increases, water fills the soil pores and provides conductive pathways for dissolved ions, thereby decreasing electrical resistance [12]. Therefore, the resistance measured by the sensor can be used as an indicator of soil water content. In addition, soil physical and chemical characteristics, such as texture, ion content, and acidity level, also affect this correlation. For example, clay soil, which is rich in minerals, has a higher cation exchange capacity than sandy soil, leading to different resistance responses even at the same moisture level [13].

2.3. Research Workflow

The research workflow was systematically designed to ensure that the result of the research objectives could be measured accurately. The process began with a literature review, followed by the design and fabrication of the soil conductivity sensor, then sensor testing, and finally data collection from experimental observations. The detailed stages and overall research workflow are presented in Figure 1.

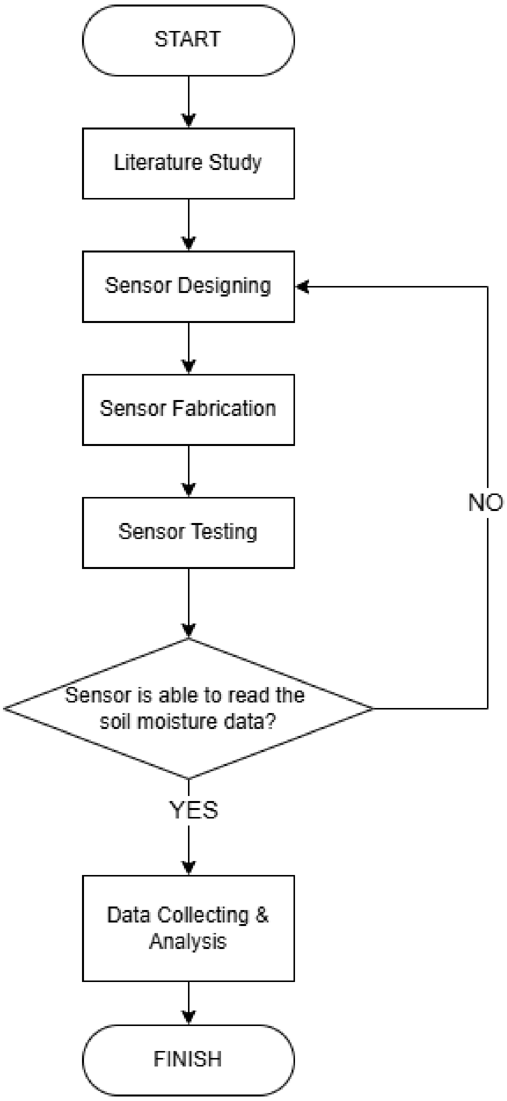

Figure 1. Workflow diagram.

2.4. Sensor Specification

The conductivity sensor used in this study was a prototype composed of a polyaniline (PANI) and graphene oxide (GO) composite, which had been prepared in previous research. This sensor utilizes the characteristics of conductive semiconductor materials that are capable of responding to soil water content in the form of changes in electrical resistance. The PANI–GO composite was applied onto a PCB substrate using the drop-casting method and then dried at a constant temperature to ensure physical and chemical stability on the sensor surface.

A copper-based electrode with an interdigitated configuration was implemented to increase the contact area between the soil and the conductive pathway, as well as to enhance the detection of electrical resistance changes. The electrode dimensions were 0.5 cm × 5 cm, with a finger spacing of 1 cm. The combination of the PANI–GO composite is expected to improve the sensor's capability to detect changes in the surrounding environment, particularly variations in soil water content.

2.5. Soil Samples

Two types of soil samples were used in this study:

- Fertile soil: obtained from an organic plantation area, visually characterized by a darker color, crumbly structure, and high natural organic matter content.
- Infertile soil: collected from degraded areas such as junkyards, dry farmland, or residential yards. This type of soil is typically lighter in color, compact, and low in nutrients.

Both soil samples were naturally dried for 48 hours and then sieved using a 2 mm mesh to obtain uniform particle size. Soil moisture variations were achieved by gradually adding water based on the dry weight of the soil to obtain four moisture levels: 10%, 20%, 30%, and 40%. The moisture adjustment was carried out using the gravimetric method by calculating the ratio of water mass to dry soil mass using a digital scale.

2.6. Testing Procedure and Data Analyzing

The tests were conducted at room temperature of 25 ± 2°C by using digital multimeter to measure changes in sensor's electrical resistance. The sensor was placed directly into the soil in a plastic container. Each measurement lasted for 5 minutes, with data recorded manually every 30 seconds. To ensure the data reliability, each testing condition was repeated three times (n=3). After each test, sensor's probe was cleaned using a lint-free cloth and dried for at least 15 minutes to avoid cross-contamination from the previous measurement.

Measurement procedure began with the preparation of soil samples according to each fertility conditions. The soil moisture level was then adjusted based on 4 predetermined levels, namely 10%, 20%, 30% and 40%. The sensor was then planted to the soil in each water contents level. The sensor electrode then measured with multimeter to obtain the resistance values from the sensor readings. The measured value were recorder every 30 seconds for five minutes for each testing condition based on the soil type and moisture level.

The resistance data obtained were then analyzed quantitatively. The mean resistance value and standard deviation from three repetitions were calculated to determine the general trend of the sensor response. Graphs illustrating the relationship between soil moisture content (%) and sensor resistance (Ω) were plotted separately to obtain the sensor response characteristics under fertile and infertile soil conditions.

A comparative analysis was also conducted to evaluate differences in sensor response sensitivity between the two soil conditions in order to assess how soil characteristics influence sensor readings. This approach is important for evaluating the sensor's ability to effectively distinguish soil moisture levels under varying environmental conditions.

3. RESULT AND DISCUSSION

3.1. Sensor Design and Fabrication

The soil conductivity sensor prototype was designed using an interdigitated electrode configuration on a flexible PET substrate. Copper electrodes with dimensions of 2 × 2 cm were patterned using screen printing or chemical etching methods, with a spacing of 0.5 mm between the electrode fingers.

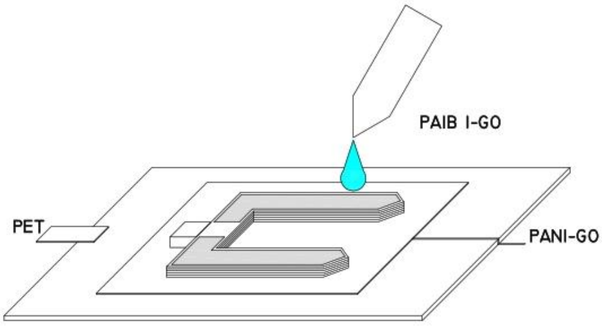

Figure 2. Drop-Casting method illustration.

The previously prepared PANI–GO composite was applied to the electrode surface using the drop-casting technique, in which the composite solution was carefully deposited to ensure uniform distribution across the inter-electrode surface.

3.2. Electrical Resistance Data in Relation to Soil Moisture Level

The test results indicate a significant relationship between soil moisture content and the resistance of the PANI–GO-based sensor. Based on the data presented in Table 1 and Figure 3, the sensor resistance tends to decrease as the soil moisture content increases in both soil types. Each testing condition was repeated three times to ensure the consistency and reliability of the measurement results.

Table 1. Average resistance value (kΩ) at various soil moisture levels.

Soil Moisture Level (%)	**Resistance Value (kΩ)**	
	Fertile Soil	Infertile Soil
10	8.7	10.4
20	6.1	8.2
30	3.9	6.0
40	2.4	4.1

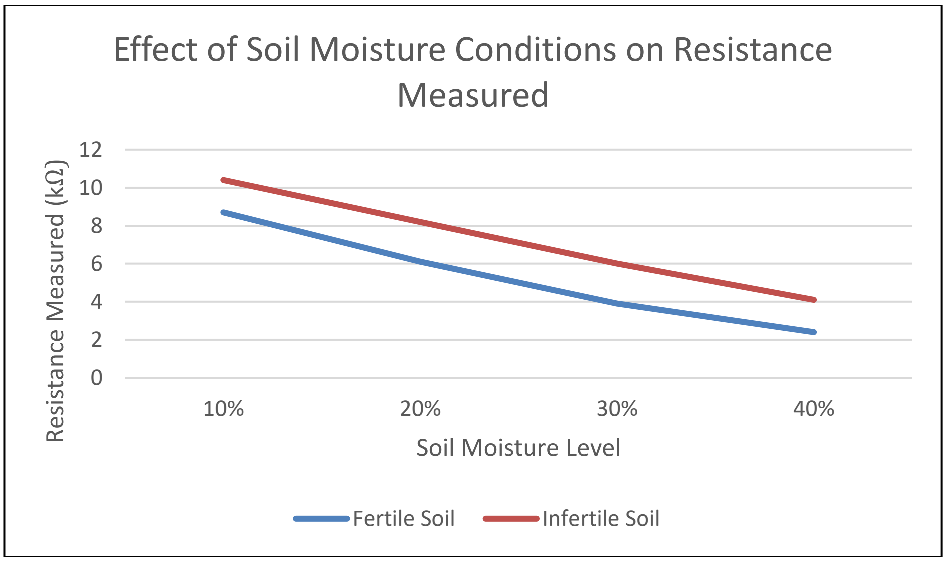

Figure 3. Correlation of soil moisture level with sensor resistance.

A consistent decrease in resistance was observed in both soil samples. This phenomenon occurs because increasing moisture content allows ions in the soil to move more easily, thereby enhancing soil conductivity and reducing the electrical resistance detected by the sensor. The

PANI–GO sensor effectively utilizes this change due to the semiconductive properties of PANI, which are sensitive to polar environments, and the presence of graphene oxide that supports charge mobility.

3.3. Sensor’s Response on Soil Condition

Although the decreasing trend in resistance appears similar, there are differences in the absolute resistance values between fertile and infertile soils. At 40% moisture content, fertile soil shows a resistance of 2.4 KΩ, whereas infertile soil remains at 4.1 KΩ. This difference can be explained by the physical and chemical composition of each soil type.

Figure 4. Soil sample in 4 different moisture levels.

Fertile soil generally contains a higher concentration of ions due to the presence of organic matter and nutrients such as K^+, Ca^{2+}, and Mg^{2+}, which enhance electrical conductivity [1]. Its crumbly and porous structure also allows water to be distributed more evenly, thereby strengthening conductive pathways between soil particles. In contrast, infertile soil, which tends to be compact and low in nutrients, exhibits lower conductivity due to the smaller number of free ions and a lower effective moisture level.

3.4. Measurement Stability

The stability test was conducted by observing the sensor response for 5 minutes under constant moisture conditions. The results show that the sensor maintained resistance values within a deviation range of ±0.2 KΩ without significant fluctuations, both in fertile and infertile soils. An example of the sensor resistance readings under soil conditions can be seen in Figure 4, which presents measurement results at 10% soil moisture. The graph forms a relatively flat line, indicating stable sensor readings during the 5-minute (300 seconds) contact between the sensor and the soil.

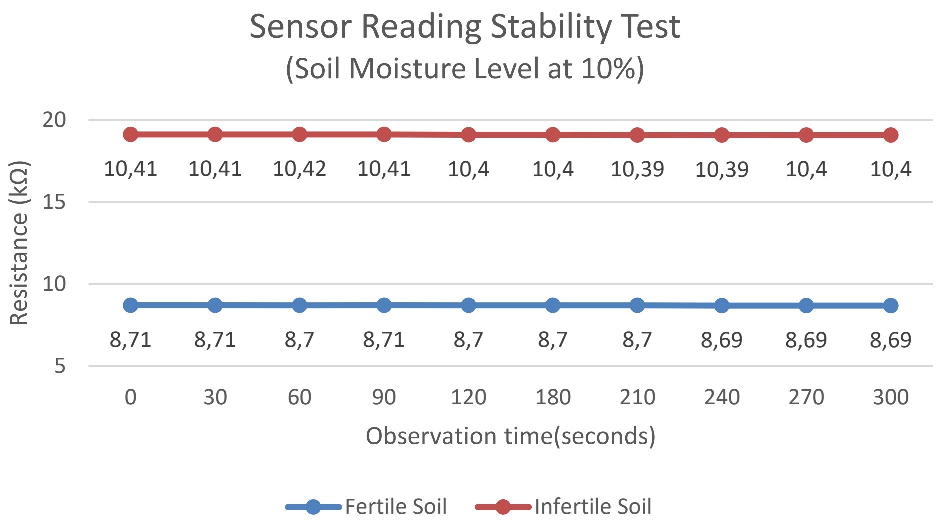

Figure 5. Stability test results of sensor readings at 10% soil moisture.

Based on the results of digital and real-time data acquisition, the sensor exhibits stable and consistent response characteristics within a relatively short observation period, indicating its potential for real-time soil moisture monitoring applications. The stability of the readings also suggests that the PANI–GO active material possesses strong chemical bonding and resistance to variations in the physical and chemical properties of soil particles during the testing process.

3.5. Application Implications

The experimental results confirm that the PANI–GO-based conductivity sensor can be used as a sensitive and stable soil moisture detection device. The proportional decrease in resistance with increasing moisture content indicates that the sensor can function as a transducer applicable to real-time soil moisture monitoring systems, particularly in supporting precision agriculture.

The different sensor performance observed in fertile and infertile soils also opens opportunities for developing more specific calibration methods, enabling the sensor to adjust resistance readings based on the soil type. Nevertheless, several limitations remain, such as measurement scalability in field conditions, sensitivity to temperature variations, and the need for integration with communication systems such as the Internet of Things (IoT) for broader applications.

4. CONCLUSION

Based on the laboratory testing results, the PANI–GO composite-based soil conductivity sensor demonstrated stable and sensitive performance in detecting variations in soil moisture, as indicated by the decrease in resistance with increasing water content. In fertile soil, the resistance decreased from 8.7 KΩ (10% moisture) to 2.4 KΩ (40%), while in infertile soil it decreased from 10.4 KΩ to 4.1 KΩ at the same moisture levels. These results indicate that the sensor is not only responsive to moisture but also capable of distinguishing conductivity characteristics between different soil types, which may be influenced by ion content and soil pore structure. The consistent sensor response within a short measurement duration also demonstrates its potential application in soil fertility-based moisture monitoring systems. Draw conclusions regarding the achievement of the objectives outlined in the Introduction. These conclusions should be presented in a narrative form, not as a list containing only numbers. Also, outline the development prospects for the research conducted.

CONFLICT OF INTEREST

The authors declare no conflicts of interest in this research.

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