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Comparative study of sensor based soil moisture detection with gravimetric method

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Abstract
Soil moisture is a crucial parameter for assessing water quantity in soil, influencing various processes such as weather, climate monitoring, flood control, crop yield estimation, reservoir management, geotechnical engineering, and water quality assessment. However, soil moisture is highly dynamic, varying significantly over time and across locations, making ground-based measurements challenging and time-consuming. Several methods exist to quantify soil moisture, such as gravimetric, nuclear, electromagnetic, tensiometric, and hygrometric techniques. Remote sensing provides an efficient alternative, but ground-based soil moisture measurements are still required at select locations. Gravimetric methods are widely used but are time-consuming and less precise compared to sensor-based approaches. Soil moisture sensors come in various types, each designed for specific applications and based on different principles. In this study, a gravimetric approach is used to compare a capacitive-type electromagnetic soil moisture sensor. Accurate soil moisture assessment is vital for field activities, as overwatering and underwatering can lead to resource inefficiencies or losses. Advancements in sensor technology have improved precision while reducing costs.

Keywords: Soil moisture, gravimetric, nuclear, electromagnetic, tensiometric, and hygrometric techniques

Introduction
Soil moisture content is a critical parameter for assessing the water quantity in soil, influencing meteorological, hydrological, agricultural, and climate-related processes. Understanding soil moisture and its spatial and temporal variations is essential for numerous applications, including weather and climate monitoring, flood control, crop yield estimation, reservoir management, geotechnical engineering, and water quality assessment. However, soil moisture is highly dynamic, varying significantly over time and across locations, making wide-scale ground-based measurements challenging, labor-intensive, and time-consuming.

Several methods exist to quantify soil moisture, such as gravimetric, nuclear, electromagnetic, tensiometric, and hygrometric techniques (Zazueta and Xin, 1994) [4]. Among these, gravimetric, hygrometric, and electromagnetic methods are commonly used. Remote sensing provides an efficient alternative, offering large-area coverage with practical, timely, and cost-effective means of soil moisture estimation. Microwave remote sensing, in particular, is the most promising technology among the electromagnetic bands for this purpose. However, ground-based soil moisture measurements are still required at select locations to calibrate and validate remote sensing data, often coinciding with satellite overpasses. Gravimetric methods are widely used but are time-consuming and less precise compared to sensor-based approaches, which are faster and more efficient. Soil moisture sensors come in various types, each designed for specific applications and based on different principles. Capacitance sensors measure the dielectric constant of the soil, offering quick and accurate readings, making them ideal for automated irrigation and precision agriculture. Resistance-based sensors, which measure electrical resistance that varies with soil moisture, are simple and cost-effective but can be influenced by soil salinity. Tensiometers measure soil water potential and are best for low to moderate moisture levels, though they require regular maintenance. Time Domain Reflectometry (TDR) sensors and Frequency Domain Reflectometry (FDR) sensors both rely on electrical signals, with TDR being highly accurate for research and large-scale applications, while FDR is more affordable for routine agricultural use. (Shukla el al. 2015) [2].

Other sensors like gypsum block sensors use embedded electrodes to measure resistance through a gypsum medium, offering a budget-friendly option for long-term monitoring, albeit with durability concerns. Neutron probes, which measure hydrogen content in the soil, provide exceptional accuracy but require regulatory approval due to their radioactive components. Gravimetric sensors, considered the gold standard, determine soil moisture by weighing samples before and after drying but are labor-intensive and primarily used in laboratory settings. Additionally, infrared sensors measure surface moisture using thermal radiation, and thermal conductivity sensors analyse heat transfer properties of the soil, both of which have niche applications. Each type of sensor comes with unique advantages and limitations, making the choice dependent on factors such as accuracy needs, soil type, and budget constraints.

In this study, a gravimetric approach is used to compare a capacitive-type electromagnetic soil moisture sensor. Capacitive soil moisture sensors take advantage of the dielectric constant between soil and water, while dry soils have a value between 2 and 6, where water has a relative permittivity of about 80% (Martinez and Barnes, 2001) [1]. Accurate soil moisture assessment is vital for field activities, as both overwatering and underwatering can lead to resource inefficiencies or losses.

Comparison is essential to understand accurate predictions of water content, as soil water volume can account for up to 60% of total soil volume, depending on its porosity (Eller and Denoth, 1996) [5]. Fortunately, advancements in sensor technology have improved precision while reducing costs. In this study, a microcontroller programmed using the Arduino platform processes the analog signal from the capacitive sensor and outputs a voltage. Using gravimetric techniques, this voltage is inversely correlated with soil volumetric moisture content. The comparison involves measuring and weighing dry and wet soil samples at various moisture levels to establish the relationship between sensor readings and soil moisture content.

2. Material and Method

2.1 Gravimetric Technique for Soil Moisture Estimation

The gravimetric technique is a widely used method for estimating soil moisture content, expressed either as a weight ratio or a volume ratio. The weight ratio is calculated as the difference in weight between wet and dry soil divided by the weight of the dry soil, while the volume ratio is determined as the volume of water relative to the total volume of the soil sample. To compute these ratios, the weight of the water in the soil sample must be obtained by drying the sample to a constant weight and measuring its mass before and after drying. The weight of the water corresponds to the difference between the wet soil and the oven-dried soil. The drying process is performed in an oven at a temperature range of 100°C to 110°C until the soil reaches a stable, constant weight, ensuring accurate measurement of the dry soil mass.

Soil Sample Collection:

Soil samples were collected from the field using a standardized method. The samples were ensured to be representative of the study area by taking them from different locations and depths, as required.

Weighing Wet Soil:

Each soil sample was weighed immediately after collection to determine its initial (wet) weight. The weight was recorded accurately.

Drying the Soil:

The soil samples were placed in pre-weighed containers and transferred to an oven. The samples were dried at a constant temperature of 105°C for 24 hours to remove moisture.

Weighing Dry Soil:

After drying, the samples were removed from the oven and allowed to cool in a desiccator to prevent moisture absorption. The dried samples were weighed, and the weight was recorded.

Calculating Soil Moisture Content:

The gravimetric method was used to calculate the soil moisture content (SMC) in percentage using the formula:

$$SMC\ (\%) = \frac{(\text{Wet weight} - \text{Dry weight})}{\text{Wet weight}} X\ 100 \qquad \text{Eq. 1}$$

Volumetric Moisture Content = Bulk density x Moisture Content Eq. 2

Data Analysis

The moisture content values for all samples were compiled. These results were compared with other variables, such as sensor data, to establish correlations or comparison.

2.2 Sensor based Soil Moisture Estimation

A sensor is a device, module or subsystem that detects events or changes in its environment and sends the information to other electronics, frequently a computer processor. The microcontroller and sensors used during the project work are shown below.

2.2.1 Soil Moisture Sensor

The capacitive type soil moisture sensor was used during the experiments. Capacitive soil moisture sensors used the working principle of a capacitor to approximate the moisture content in soil. The sensor used for the comparison and analysis was depicted in Figure 1. This capacitive moisture sensor converted its resonance frequency to an analog signal using a 555-timer integrated circuit, which an Arduino board was then read. In order to establish an empirical connection between the soil moisture and the sensor's output analog signal, this signal was compared.

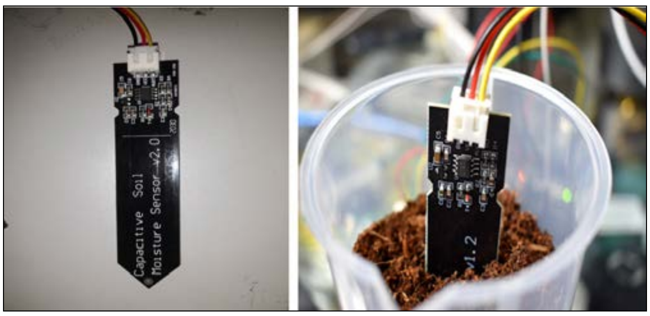

Fig 1: Capacitive soil moisture sensor inserted into the test soil.

The Arduino board in use was an Arduino Uno, which featured an external reference and a 10-bit bit analog to digital convert (ADC) that ran at 3.3V. The capacitive sensor used was only effective between around 1.5V and 3.3V, even though it worked at 3.3V. This indicated that the actual operable range was only roughly 50%. With a VWC measurement range of 0% to 100% and an operational range of 1.5V to 3.3V, the 10-bit ADC provided a VWC resolution of roughly 0.5%, which was the measurement setup's bottom limit on resolution. Although a higher resolution ADC would have yielded a better measurement resolution, the existing analysis succeeded with only 10 bits.

Figure 2 shows the capacitive soil moisture sensor wiring to Arduino Uno board. The components of this experiment measured the weight and volume of soil, both wet and dry, in order to capture the two fundamental concepts utilized in calibrating soil moisture sensors.

2.2.2 Microcontroller Chipset

A compact computer on a single integrated circuit is called a microcontroller (MC) or microcontroller unit (MCU). One or more CPUs (processor cores), memory, and programmable input/output peripherals are all found in a microcontroller. Unlike microprocessors, which are made up of different discrete chips and are utilized in personal computers and other general-purpose applications, microcontrollers are made for embedded applications.

Microcontroller chipset, NodeMCU ESP-8266 is used. This module allows microcontrollers to connect to a Wi-Fi network. NodeMCU is an open-source Lua based firmware and development board specially targeted for IoT based Applications. It includes firmware that runs on the ESP8266 Wi-Fi SoC from Espress if Systems, and hardware which is based on the ESP-12 module.

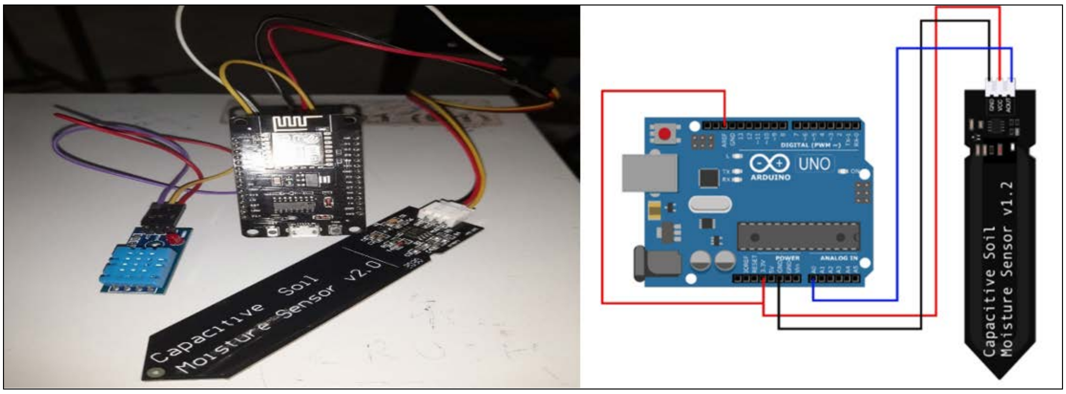

Fig 2: Capacitive soil moisture sensor wiring to Arduino Uno board.

2.3 Comparison of soil moisture sensor

For the calibration of the soil moisture sensor, a soil sample was collected from the field.

- A 100g soil sample was placed in each of the glasses numbered 1 to 10. Corresponding amounts of water 10 ml, 20 ml, 30 ml, up to 100 ml were poured into the glasses.
- The soil moisture sensor readings were observed from soil samples.
- Soil samples were then taken from the glasses and placed in an oven for 24 hours at 105 °C.
- The weight of the dried sample was determined using the gravimetric method to measure the actual soil moisture present.
- Finally, the sensor data was plotted against the gravimetric soil moisture data.

3. Result and Discussion

The study presents a comparative evaluation of soil moisture estimation using gravimetric techniques and sensor-based methods. Both approaches have distinct methodologies, yielding critical insights into soil moisture dynamics.

3.1 Gravimetric Technique Results

The gravimetric method, regarded as one of the most accurate techniques for soil moisture estimation, involves drying soil samples to constant weight in an oven at 100 °C-110 °C. The difference in wet and dry weights provides the weight ratio, which can be translated to volumetric moisture content. The results from this method offer precise baseline measurements against which sensor outputs are compared.

Table 1: Comparision of volumetric and capacitive moisture content

Wet sample weight (g)	Dry sample weight (g)	(Wet Basis-Dry Basis) / Wet Basis	Moisture Content (%)	Volumetric Moisture Content	Capacitive Moisture Content
28.06	26.36	0.06	6.06	9.09	23
29.18	27.09	0.07	7.16	10.74	30
27.16	24.73	0.09	8.95	13.42	54
28.84	25.84	0.10	10.40	15.60	63
30.33	26.90	0.11	11.31	16.96	72
27.96	23.95	0.14	14.34	21.51	79
28.68	24.72	0.14	13.81	20.71	82
28.17	23.69	0.16	15.90	23.86	91
28.98	23.35	0.19	19.43	29.14	91
28.63	23.08	0.19	19.39	29.08	91

The experimental data, as tabulated, shows a progressive increase in moisture content as wet sample weights increase. For example, the wet sample weighing 28.06g and a dry weight of 26.36g corresponds to a moisture content of 6.06%. Similarly, at higher moisture levels, such as a wet sample weight of 28.63g and a dry weight of 23.08g, the moisture content rises to 19.39%. This trend aligns with expectations, as the difference between wet and dry weights directly relates to the moisture present in the sample.

3.2 Sensor-Based Estimation with IoT Integration

The capacitive soil moisture sensor compared using an Arduino Uno and NodeMCU ESP-8266 microcontroller provides an innovative and dynamic approach to soil moisture monitoring. The sensor operates effectively within a voltage range of 1.5V to 3.3V, with a volumetric water content (VWC) measurement range of 0%-100%. While its 10-bit ADC offers a resolution of approximately 0.5%, higher resolutions could enhance precision.

The comparison process involved correlating the sensor's analog output with gravimetric measurements. Soil samples were subjected to controlled water additions, dried in an oven, and weighed to establish empirical relationships between sensor readings and actual moisture levels. Data from the soil moisture senser indicate moisture readings are closely aligned with gravimetric estimates, though some discrepancies are noted at higher moisture levels. For instance, gravimetric moisture content of 29.08% corresponds to a soil moisture sensor reading of 91%. This divergence may stem from the sensor's operational range limitations or calibration constraints.

3.3 Graphical Analysis and Observations

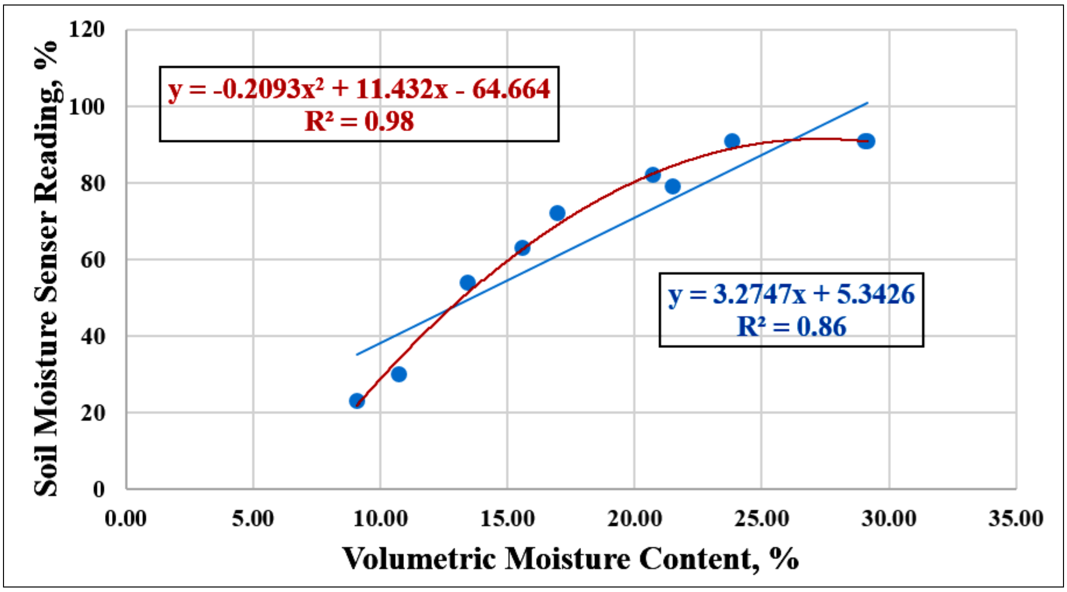

Fig 3: Soil Moisture sensor reading and Volumetric moisture content

Figure 3 illustrates the relationship between soil moisture sensor readings and volumetric moisture content. The correlation coefficient of 0.86 (linear trendline), 0.98 (Polynomial trendline) suggests strong agreement between sensor outputs and gravimetric measurements, validating the sensor's efficacy under field conditions. However, sensor readings exhibit a plateau effect at higher moisture levels, reflecting saturation of the sensor's operable range. The study demonstrates the feasibility of integrating capacitive sensors with real-time soil moisture monitoring, highlighting their potential in precision agriculture. While the gravimetric method remains the benchmark for accuracy, sensor-based systems provide scalable and cost-effective solutions for dynamic environments.

Future improvements could involve employing higher-resolution ADCs and advanced calibration techniques to enhance sensor accuracy. Additionally, exploring alternative sensor designs, such as resistive or thermal sensors, may offer better performance across diverse soil types and conditions. While gravimetric methods establish accuracy benchmarks, sensor technologies integrated with IoT pave the way for real-time, large-scale monitoring, addressing critical needs in agriculture and environmental management.

4. Conclusion

- The analysis of the given data reveals significant discrepancies between the Sensor-based soil moisture sensor (SMS) and the gravimetric moisture measurement (GMM), particularly at higher moisture content levels.
- While the SMS shows reasonable alignment with GMM values at lower moisture levels, its accuracy deteriorates as the moisture content increases, with the maximum deviation in moisture content in senser data.
- This trend suggests potential calibration issues or non-linear behaviour of the sensor at elevated moisture levels.
- The calculated "Moisture Content * Bulk Density" values exhibit consistency and proportionality to the GMM, indicating that bulk density is accurately accounted for in these calculations. However, the SMS performance remains highly variable, especially under conditions of high soil moisture content.
- These observations highlight the critical need for calibration of the sensor, particularly for scenarios involving higher moisture levels. Correlation coefficient of 0.86 (linear trendline), 0.98 (Polynomial trendline) suggests strong agreement between sensor outputs and gravimetric measurements and this model is acceptable for low moisture content is available in soil.
- To address these discrepancies at higher moisture level, it is recommended to recalibrate the SMS using a more extensive and diverse dataset of soil samples. Additionally, potential causes for non-linearity, such as sensor saturation or environmental factors influencing dielectric measurements, should be investigated. Incorporating advanced machine learning algorithms or regression

techniques may also improve the sensor's predictive accuracy and overall performance.

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