Design and Development of Capacitive Sensor System using WSN for Precise Monitoring of Soil Moisture

The project report submitted in partial fulfillment of the requirement for the degree of

Bachelor of Technology

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CERTIFICATE

This is to certify that the thesis entitled "**Design and Development of Capacitive Sensor system using WSN for Precise Monitoring of Soil Moisture**" submitted by Ashique Anowar (200610026010), Anirban Biswas (200610326008), Ritav Kashyap (200610326078) and Rohan Verma(200610026045) in the partial fulfillment of the requirements for the award of Bachelor of Technology degree in Electronics & Telecommunication at Assam Engineering College, Jalukbari, Guwahati is an authentic work carried out by them under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

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DECLARATION

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ABSTRACT

The creation of a sophisticated capacitive soil moisture sensor is deemed essential to the goals of precision and sustainable agriculture. The purpose of this sensor is to meet the growing needs of agricultural activities for accurate soil moisture monitoring and effective water management. The project is centered on the design, development, and use of a capacitive sensor that makes use of cutting-edge technology to improve soil moisture measurement accuracy and dependability. A sensor probe is made with a sensing system for effective soil moisture monitoring since the soil's ability to store water varies based on its structure. The developed sensor probe is calibrated for three distinct soil types (silt, sandy, and clay) using gravimetric analysis. To handle the sensor data, we designed a circuit having an ATmega328 microcontroller to process data (basically converting sensor response into capacitance and moisture percentage), a display to show the moisture percentage and a Bluetooth module to transmit data to other devices as well. The Capacitive Soil Moisture Sensor created in this research is an important step towards a more resilient and efficient agricultural future.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Sensors are used in many important applications like medical equipment, industrial control systems, air-conditioning systems, aircraft and satellites. They work by converting physical parameters such as temperature, pressure and wind speed into an electrical output that can be visualized by an observer. Capacitive sensors provide an alternative to the traditional mechanical buttons and sliders in electronics. These sensors work by sensing a conductive object nearby rather than detecting the physical state of the device.

Soil moisture is a crucial parameter in the fields of agricultural, geotechnical, hydrological, and environmental engineering. For precision agriculture, the scheduling of irrigation is highly dependent on soil moisture content and plant environment. The interdigital sensor concept is now widely used for soil moisture measurement. With advances in printed circuit board (PCB) technology, it is now easier to develop this kind of sensor for various applications.

Capacitive sensing is a dominant technique for soil moisture measurement. The design of capacitive sensors for such applications by shape optimization is of research interest. For designing an interdigital sensor, three design parameters should be accounted for: 1) thickness of the electrodes; 2) separation of two adjacent electrodes; and 3) thickness of the base material.

1.2 Motivation

The Soil Moisture Capacitive Sensor project was born out of the profound challenges that farmers face, which are exacerbated by the erratic nature of climatic conditions and the need for precise irrigation strategies. In a landscape marked by the unpredictability of weather patterns, the agricultural sector is dealing with the consequences of water scarcity, which has a significant impact on crop yield and overall productivity. The impetus for this project arose from a genuine and pressing desire to provide farmers with a dependable tool for monitoring soil moisture levels. The inspiration for this project came from the struggles of local farmers, whose livelihoods are inextricably linked to the ebb and flow of water availability. The project team gained valuable insights into the profound impact of water scarcity on agricultural outcomes through intimate conversations with these farmers. The consensus was unanimous: a low-cost, accurate, and easily deployable soil moisture-sensing solution was an unmet need with the potential to transform farming practices.

The Soil Moisture Capacitive Sensor project is motivated by a desire to address pressing agricultural issues. Its goal is to provide farmers with a technology-driven solution for increasing resilience against unpredictable weather patterns and improving irrigation efficiency. The project aims to bridge the gap between technological innovation and the practical needs of those working on the land, contributing to sustainable agriculture. It is inspired by firsthand experiences and stories of resilience from the farming community.

1.3 Objectives

By developing an innovative and power-efficient capacitive soil moisture sensor, this project aims to make significant advances in precision farming and the integration of the Internet of Things (IoT). Recognising the importance of soil moisture in agricultural productivity, this initiative seeks to overcome the limitations of traditional resistive soil moisture sensors through the use of advanced capacitive sensing technology.

The primary objectives of this project are to thoroughly investigate the performance of three distinct capacitive soil moisture sensor models—Model A, Model B, and Model C—each made of copper, aluminum, and silicon, respectively, by analyzing and quantifying their responses to varying soil moisture levels. The study aims to uncover complex patterns and trends in the relationship between soil permittivity and capacitance for each material, providing actionable insights for precision farming. In the second phase, the project focuses on developing and fabricating the model with the best linearity trend 'r' (correlation coefficient), ensuring the most accurate moisture content measurement. This prototype, utilizing capacitive sensing, aims to deliver reliable soil moisture readings, reduce water waste, improve crop health, and maintain ideal moisture levels for enhanced plant growth and yield. Additionally, the project seeks to offer an affordable sensor solution for farms of all sizes, contributing to water conservation, sustainable agriculture practices, and long-term soil quality preservation.

The overarching goal is to highlight the practical benefits of a novel sensor technology in the context of agriculture. The project seeks to establish the superiority of capacitive sensing over resistive methods through a thorough examination of simulation data, particularly in terms of energy efficiency and precision. The report will provide recommendations and strategic insights for the seamless integration of capacitive soil moisture sensors into precision farming practices, focusing on the potential for real-time monitoring, resource optimisation, and informed decision-making in agricultural settings. By achieving these goals, the project hopes to have a significant impact on the efficiency and sustainability of modern farming practices.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Various esteemed scholars and sensor companies have periodically produced several versions of Soil Moisture Sensors to measure the water level in the Soil. With a focus on capacitive sensors, this report explores various methodologies, sensing principles, and advancements made in the field. It critically analyzes previous works, identifying strengths, weaknesses, and gaps in current knowledge. By delving into the existing literature, this section aims to establish a solid foundation for the Soil Moisture Capacitive Sensor project, drawing on insights from prior studies to inform the design, implementation, and evaluation phases of the project.

2.2 Literature Review

Calibration of Capacitive Soil Moisture Sensor (SKU:SEN0193)[2] by Radi et al. in 2018 addresses the essential objective of calibrating a specific capacitive soil moisture sensor, SKU:SEN0193, tailored to local soil conditions. The primary focus of the study is to understand the sensor's response to varying moisture levels within soil samples and subsequently establish calibration equations. These equations are formulated to account for different treatment conditions, such as soil volume and temperature. The outcome of the research delves into the detailed analysis of calibration results, presenting sensor-specific equations under diverse environmental conditions. Notably, the study emphasizes the validation of these calibration equations through correlation analysis and error measurements. An intriguing finding reveals that the sensor's responsiveness remains robust, showing negligible impact from variations in soil volume and only a slight influence from ambient temperature conditions. This insightful investigation provides valuable contributions to the field of soil moisture sensing, offering practical insights for the accurate calibration of capacitive sensors under varying environmental factors.

A Capacitive Soil Moisture Sensor[3] H. Eller and A. Denoth, dated 22nd February 1999, is a pivotal contribution to the field of soil moisture measurement. The primary objective of the article is to underscore the importance of accurate soil moisture assessment across various applications. In doing so, the study critically evaluates existing measurement methods such as thermogravimetry, time domain reflectometry (TDR), and electromagnetic techniques. Recognizing the limitations of these methods, the paper introduces an innovative approach—a portable battery-powered dielectric probe relying on impedance measurements. The research meticulously characterizes soil dielectric properties, identifies an optimal operating frequency (32 MHz), and validates the probe's performance through comparative measurements and practical field applications. The key outcome of the study is the successful demonstration that soil moisture content can be precisely measured using the developed capacitive sensor, presenting complex permittivity at the specified frequency. The sensor, operational at 32 MHz, proves to be highly suitable for field measurements, yielding results with a relative error of approximately 5% or less. This research not only introduces a novel soil moisture measurement technique but also establishes its practical efficacy for on-site applications.

Design and Characterization of a Fringing Field Capacitive Soil Moisture Sensor[1] authored by M. Protim Goswami, B. Montazer, and U. Sarma in March 2019, is a significant contribution to the advancement of soil moisture sensing technology. The primary objective revolves around the development and characterization of a fringing field capacitive soil moisture sensor employing PCB technology. The abstract introduces a novel interdigital sensor design, emphasizing optimization through simulation and practical fabrication. Performance assessment is conducted by comparing sensor measurements with the standard gravimetric method across diverse soil samples. Three distinct models are presented: Model 1 with electrodes arranged in an interpenetrating comb pattern on one side of an FR4 board, Model 2 incorporating a copper-covered back side to minimize moisture influence, and Model 3, a novel configuration with electrodes on both sides for a larger sensing area. Model 3 demonstrates superior sensitivity compared to the other models. Dynamic tests reveal that Model 1 exhibits the fastest response time, followed by Model 3, while Model 2 shows the slowest response time. This research not only introduces innovative sensor designs but also provides a comprehensive comparative analysis of their performance, offering valuable insights for future advancements in fringing field capacitive soil moisture sensors.

2.3 Theoretical Discussion

Capacitive soil moisture sensors represent a significant advancement over traditional resistive soil moisture sensors, primarily due to their non-destructive nature and enhanced reliability. While resistive sensors measure moisture content based on the resistance between two electrodes, capacitive sensors gauge moisture levels by detecting changes in the dielectric permittivity of the soil, which alters the capacitance of the sensor. This method eliminates issues such as electrode corrosion and degradation that can plague resistive sensors, leading to more accurate and long-lasting performance. In our project, we designed three distinct sensor models using copper, aluminum, and silicon, each with varying fringing field patterns, to identify the most effective material and design for precise soil moisture measurement. The investigation revealed that the model utilizing copper with a honeycomb-like structure fringing field pattern offered the highest correlation coefficient, indicating superior performance in detecting soil moisture levels.

The application of capacitive sensing in soil moisture measurement has numerous advantages, including the ability to reduce water waste and improve crop health by maintaining optimal soil moisture levels. Capacitive sensors are highly sensitive to changes in soil moisture, providing accurate and reliable data that farmers can use to make informed irrigation decisions. This capability is crucial for precision farming, where the goal is to maximize yield and resource efficiency. Our project demonstrates this through a prototype that integrates advanced features such as an OLED display for real-time capacitance visualization and a Bluetooth module for data transmission to a mobile app. This makes the sensor both affordable and versatile, catering to farms of all sizes. By ensuring that crops receive just the right amount of water, the sensor contributes to water conservation efforts and promotes sustainable agricultural practices. Additionally, maintaining ideal moisture levels helps preserve soil quality, which is vital for the long-term viability of farming operations.

Compared to existing solutions, our project offers significant improvements in accuracy and reliability. For instance, Mizuguchi et al.[7] (2014) reported a coefficient of determination of 0.94 using a gravimetric method for calibration, while Nagahage et al.[8] (2019) achieved a goodness of fit value of 0.98 compared to a standard SM-200 sensor. In contrast, our sensor probe, calibrated using a gravimetric method, achieved an average goodness of fit value of 0.99 for voltage and capacitance responses across six different soil types. This high level of accuracy is further enhanced by the use of the SBM algorithm, which derives calibration equations from voltage responses, ensuring precise moisture content measurements. These improvements demonstrate that our capacitive soil moisture sensor not only surpasses the performance of existing models but also addresses common issues related to soil moisture measurement, offering a robust solution that supports sustainable and efficient farming practices.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In the fields of environmental and agricultural sciences, accurate soil moisture monitoring is essential to maximizing irrigation efficiency and advancing sustainable practices. Fringe field capacitive soil moisture sensors, which rely on fluctuations in soil dielectric characteristics and changes in capacitance, have become useful instruments. This introduction explains how to develop such sensors using the powerful finite element analysis program COMSOL Multiphysics. Understanding the theory of fringing field capacitive sensing is the first step. COMSOL is used to analyze the distribution of the electric field and variations in capacitance within the sensor geometry.

This report shows a linear relationship between moisture content and fringing capacitance. For designing an interdigital sensor, three main design parameters should be accounted for: 1) the thickness of the electrodes; 2) the separation between two adjacent electrodes; and 3) the thickness of the base material. The fringing field capacitive sensor is a dominant field for various sensing applications such as water-level measurement, soil water content measurement, moisture content of various agricultural commodities, and moisture content of wood pallets. Due to water's high relative permittivity, it provides a considerable change in capacitance by interacting with the interdigital capacitive sensors. A fringing field capacitor consists of multiple capacitive plates on the same plane, arranged in an interpenetrating comb pattern.

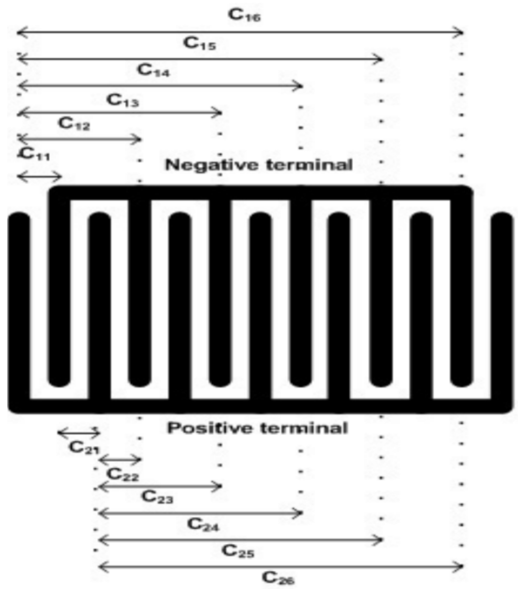


Fig 3.1: Interdigital sensor pattern

The operating principle of a planar interdigital sensor is based on the same principle as that of a parallel-plate capacitor, where one side of the electrodes is exposed to the materials being tested. Therefore, it can be considered as a number of capacitors arranged in a parallel manner with n numbers of electrodes. For the first positive electrode, capacitance will be C11, C12, C13,......,C1n for 1,2,3,.......,n negative electrodes, respectively. For the second positive electrode, capacitance will be C21, C22, C23,........,C2n for 1,2,3,........,n negative electrodes, respectively. Similarly, for the 'm' positive electrodes, capacitance will be Cm1, Cm2, Cm3,........Cmn for 1,2,3,......,n negative electrodes respectively. Thus, the equivalent capacitance of the electrodes is as follows:

$$C1(eq) = C11 + C12 + C13+ \ldots\ldots\ldots + C1n$$

$$C2(eq) = C21 + C22 + C23+ \ldots\ldots\ldots + C2n$$

$$C3(eq) = C31 + C32 + C33+ \ldots\ldots\ldots + C3n$$

……

……

$$Cm(eq) = Cm1 + Cm2 + Cm3+ \ldots\ldots\ldots + Cmn$$

Therefore, the total capacitance of the sensor is:

$$C(total) = C1(eq) + C2(eq) + C3(eq)+ \ldots\ldots\ldots + Cm(eq)$$

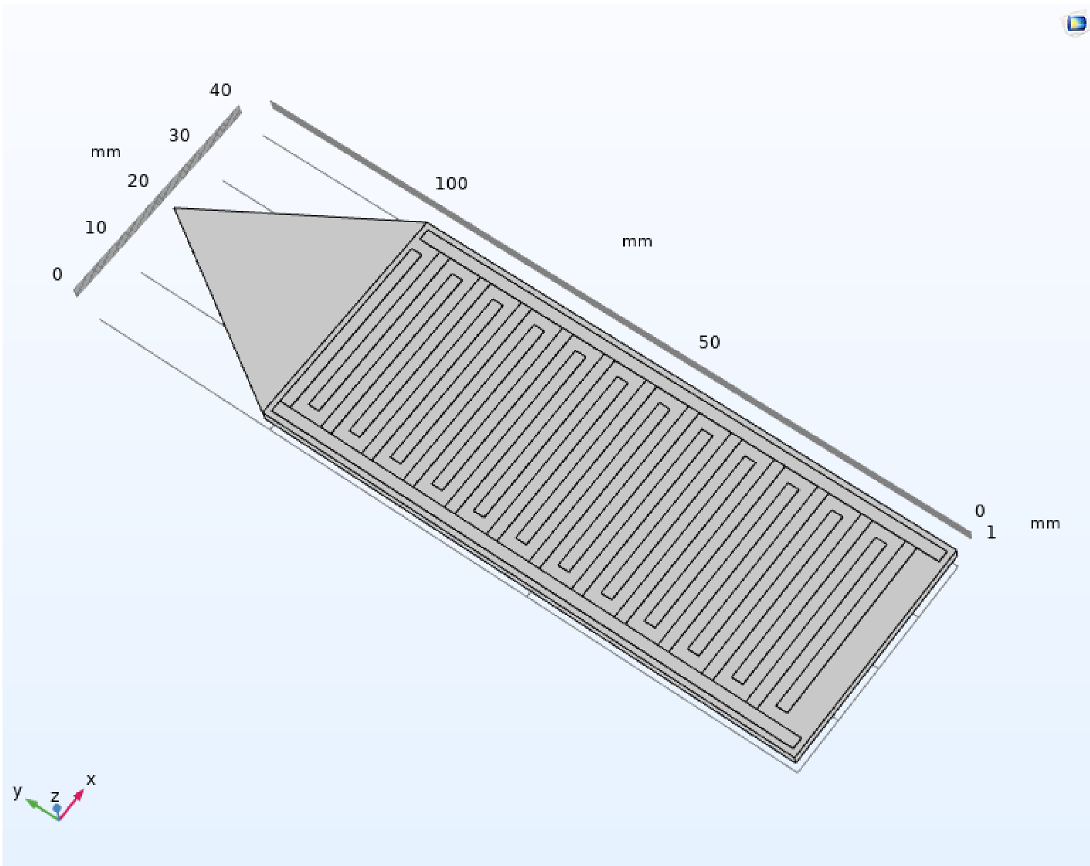
3.2 Methodology

During the first phase of our capacitance soil moisture sensor project, we concentrated on creating a basic model with various dimensions that included fringing patterns and copper, silicon, and aluminum traces. To imitate real-world settings, we developed three distinct sensor models, each of which was contained in a sphere. The mesh creation technique was critical to correctly reflecting the sensor geometries and surrounding material. Using COMSOL Multiphysics, we ran simulations to produce datasets of capacitance values for various soil moisture levels. The primary purpose was to find the sensor model with the best linear trend, as defined by the correlation coefficient 'r', to achieve our project's goals.

The sensor model that showed the ideal linearity 'r' from the COMSOL simulations was constructed in the second step. This model has a fringing field design and a structure like a honeycomb. Preparing the substrate, transferring the circuit design, and etching the patterns onto the sensor material were some of the phases in the fabrication process. After the gadget was fabricated, we moved on to the circuit design, using an ATmega328 microcontroller to run our apparatus. Furthermore, we incorporated a Bluetooth module to provide wireless soil moisture level monitoring using a mobile application. This configuration made our sensor both practical and efficient by enabling real-time data transfer and user-friendly interaction.

3.2.1 Designing of Model A

In the initial stages of designing Model A[1] in COMSOL Multiphysics, the process commences by creating a rectangular pattern with specified dimensions of 100mm x 20mm and a thickness of 2mm. This foundational structure serves as the base for subsequent fringing field capacitive soil moisture sensor development. The material definition for this substrate is crucial, and in this case, the choice is the commonly used FR4 board, known for its favorable electrical properties and widespread use in electronics. The next critical step involves configuring the fringing field pattern on the substrate. Utilizing COMSOL's versatile tools, a design is implemented, incorporating specific dimensions for the fringing field traces, each with a thickness of 0.1mm. This intricate pattern is a key determinant in the sensor's performance, as it facilitates the interaction between the electric field and the soil, allowing for accurate moisture measurements. The uniqueness of this design lies in its adaptability for material exploration. To comprehensively understand and optimize the sensor's characteristics, three distinct models are created, each time altering the material composition of the fringing field pattern. The materials under consideration are copper, aluminum, and silicon, each possessing unique electrical properties that influence the sensor's capacitance response to soil moisture variations. Copper, known for its excellent conductivity, is evaluated for its potential to enhance the sensor's sensitivity. Aluminum, chosen for its lightweight nature and good electrical conductivity, presents an alternative that may exhibit different characteristics compared to copper. Silicon, with its semiconductor properties, adds another dimension to the exploration, potentially impacting the sensor's performance in various ways.



.Fig 3.2: Structure of Model A

Following the establishment of the model's base and intricate fringing field pattern, a pivotal step involves encapsulating the entire structure within a circular hollow sphere. This sphere is designated as a blank material, serving as the encapsulating environment for the moisture sensor. This carefully constructed environment is instrumental in facilitating the sensor's operation, creating a controlled setting for accurate simulations. During the simulation phase, a noteworthy adjustment is made by altering the permittivity of the hollow sphere. This deliberate modification directly influences the capacitance values within the sensor, reflecting the dynamic interaction between the sensor and its surrounding environment. The hollow sphere, acting as a representation of the soil or external medium, allows for a realistic portrayal of the sensor's behavior under varying moisture conditions. The ability to dynamically manipulate the permittivity of this environment within COMSOL Multiphysics introduces a level of adaptability crucial for accurately capturing the sensor's response to changing soil moisture levels.

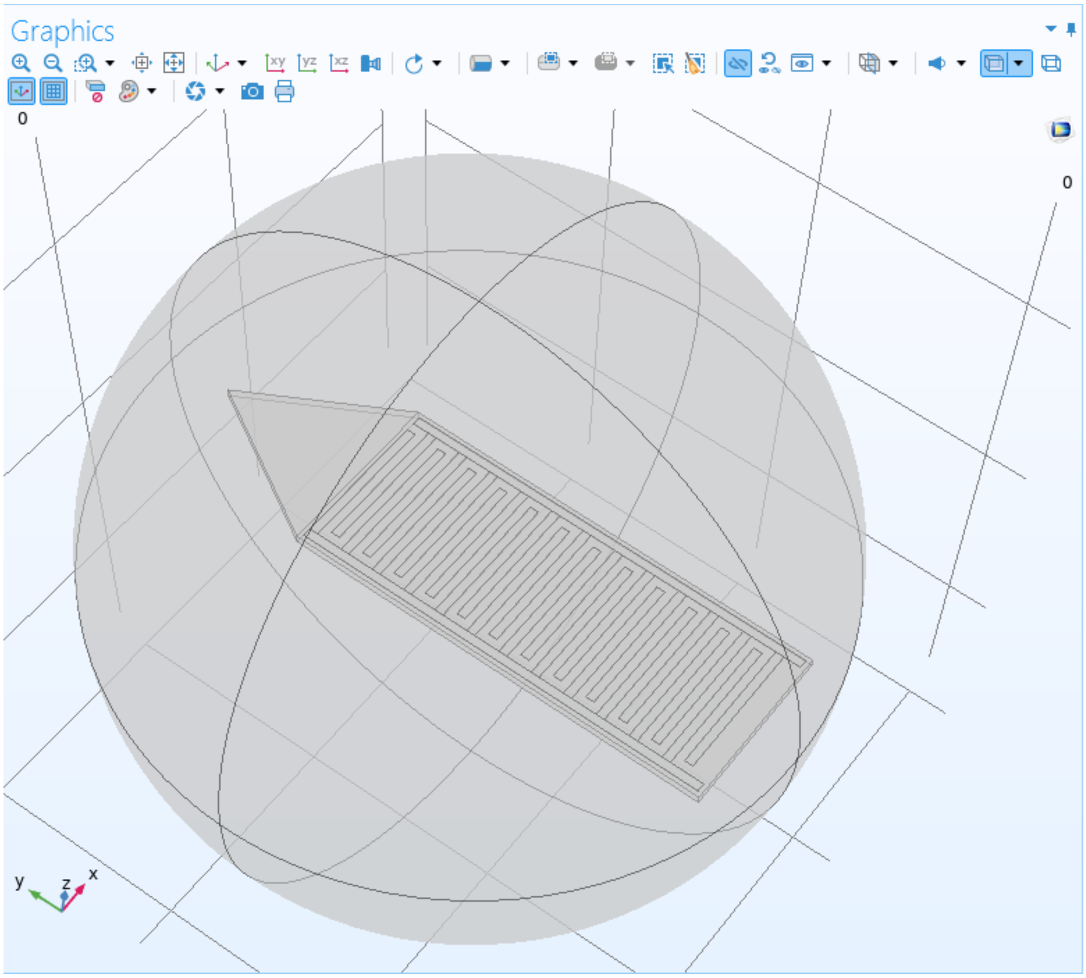


Fig 3.3: Enclosed Environment for Model A

After the environmental encapsulation, the first compute step is to carefully create a mesh in COMSOL Multiphysics using the pre-specified physics parameters. A very fine mesh configuration is used, with an even higher degree of precision. This thoughtful decision optimizes the accuracy of the simulation results by ensuring a finely meshed model. This level of mesh refinement allows the computational model to accurately represent the complex geometry and material interactions of the fringing field capacitive soil moisture sensor. The most precise and trustworthy capacitance values can only be obtained with such accuracy in meshing, which also helps to provide a thorough understanding of the sensor's performance in a range of material and environmental circumstances.

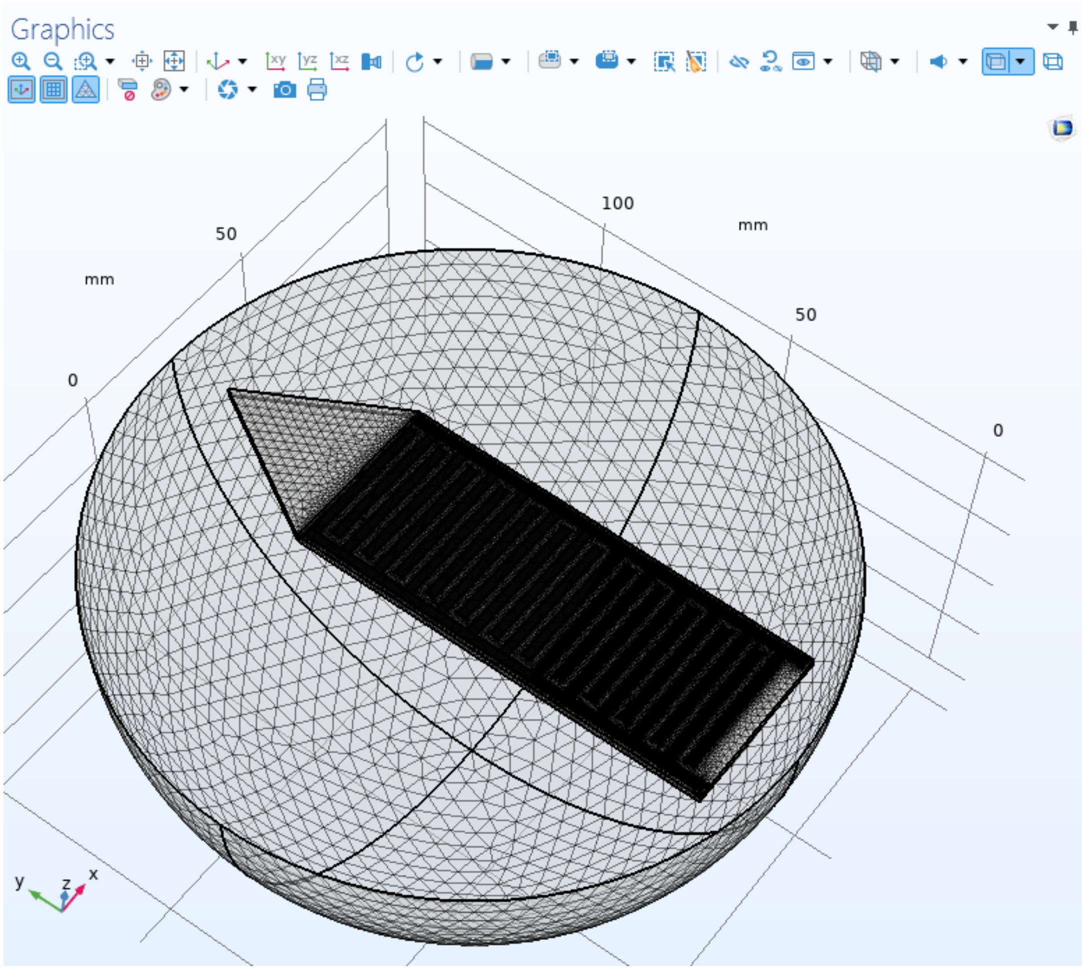


Fig 3.4: Mesh of Model A

In the concluding processing steps, the physics of the fringing field capacitive soil moisture sensor model are meticulously defined within COMSOL Multiphysics. The permittivity of the fringing pattern, a pivotal parameter, is set based on the material employed. Notably, copper, aluminum, and silicon exhibit distinct permittivity values of 1, 6, and 11.6[6], respectively. This differentiation accounts for the materials' electrical characteristics, contributing to the unique capacitance responses of the sensor. Subsequently, two terminals representing charges of +1C and -1C are defined, simulating the electrical configuration of the sensor. The final computational phase is initiated, wherein each iteration involves the systematic adjustment of the permittivity values of the hollow sphere.

Throughout these iterations, the model undergoes computations that dynamically alter the environmental permittivity, capturing the sensor's behavior across a spectrum of moisture levels. The culmination of these computations results in a comprehensively processed model, delineating how the sensor reacts under different conditions. In the sidebar, the software visually represents the electric potential, providing insights into the current flow and other crucial aspects of the sensor's operation. This graphical representation enhances the user's understanding of the model's behavior, enabling a detailed analysis of electric potential distribution and its correlation with capacitance variations.

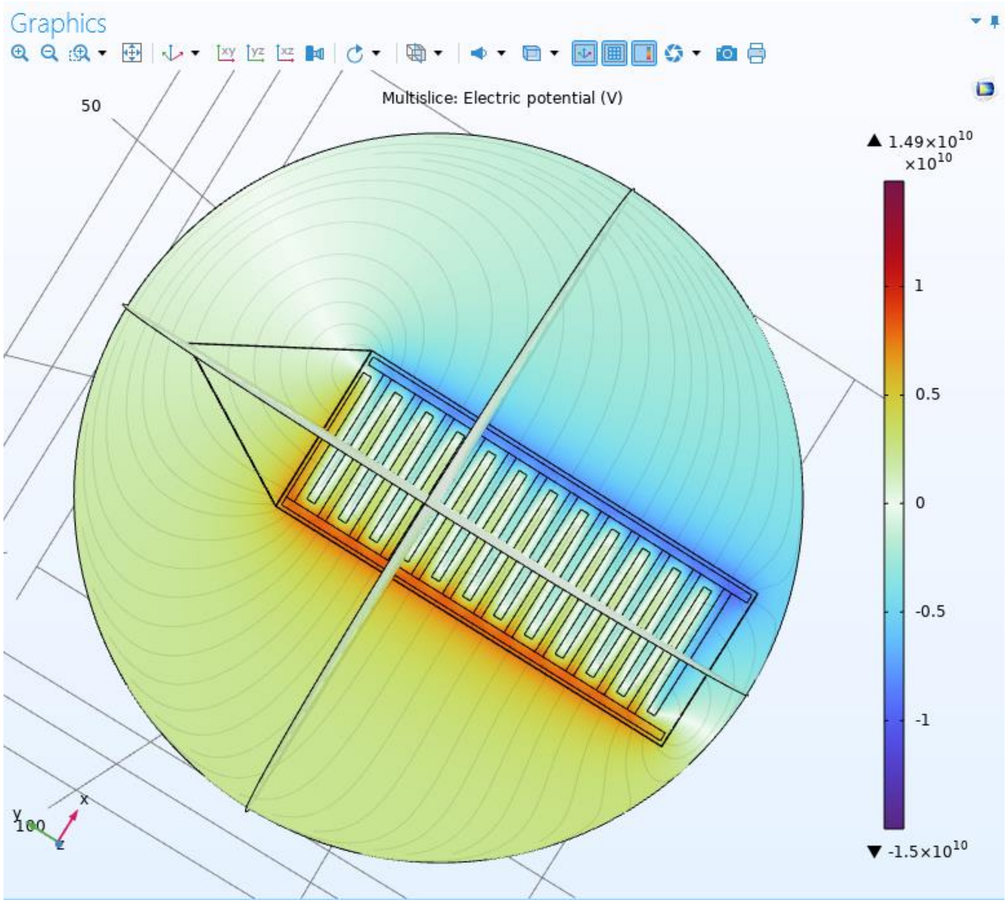


Fig 3.5: Computation of potential for Model A

3.2.2 Designing of Model B

Model B in COMSOL Multiphysics starts with the creation of a Square configuration with dimensions of 50 × 50 mm and 2 mm in thickness. The following construction of a capacitive soil moisture sensor, with particular attention on the fringing field element, is made possible by this basic structure. The choice of substrate material is crucial, and the most popular option is the FR4 board, which is known for its excellent electrical properties and widespread use in electronic applications. The formation of the fringing field pattern on the substrate is the next crucial stage. Using the flexible tools that COMSOL offers, a design is put into practice that introduces precise dimensions for the fringing field traces, each of which has a thickness of 0.1mm.

What sets this design apart is its adaptability for material exploration. To gain a comprehensive understanding and optimize the sensor's attributes, three distinct models are crafted, each involving a modification of the material composition within the fringing field pattern. The materials under scrutiny are copper, aluminum, and silicon, each characterized by distinct electrical properties influencing the sensor's capacitance response to changes in soil moisture. In each iteration of the model, the simulation within COMSOL Multiphysics entails a thorough analysis of the electric field distribution and capacitance variations within the sensor geometry. This simulation-centric methodology facilitates the assessment and comparison of the sensor's behavior under varying material scenarios.

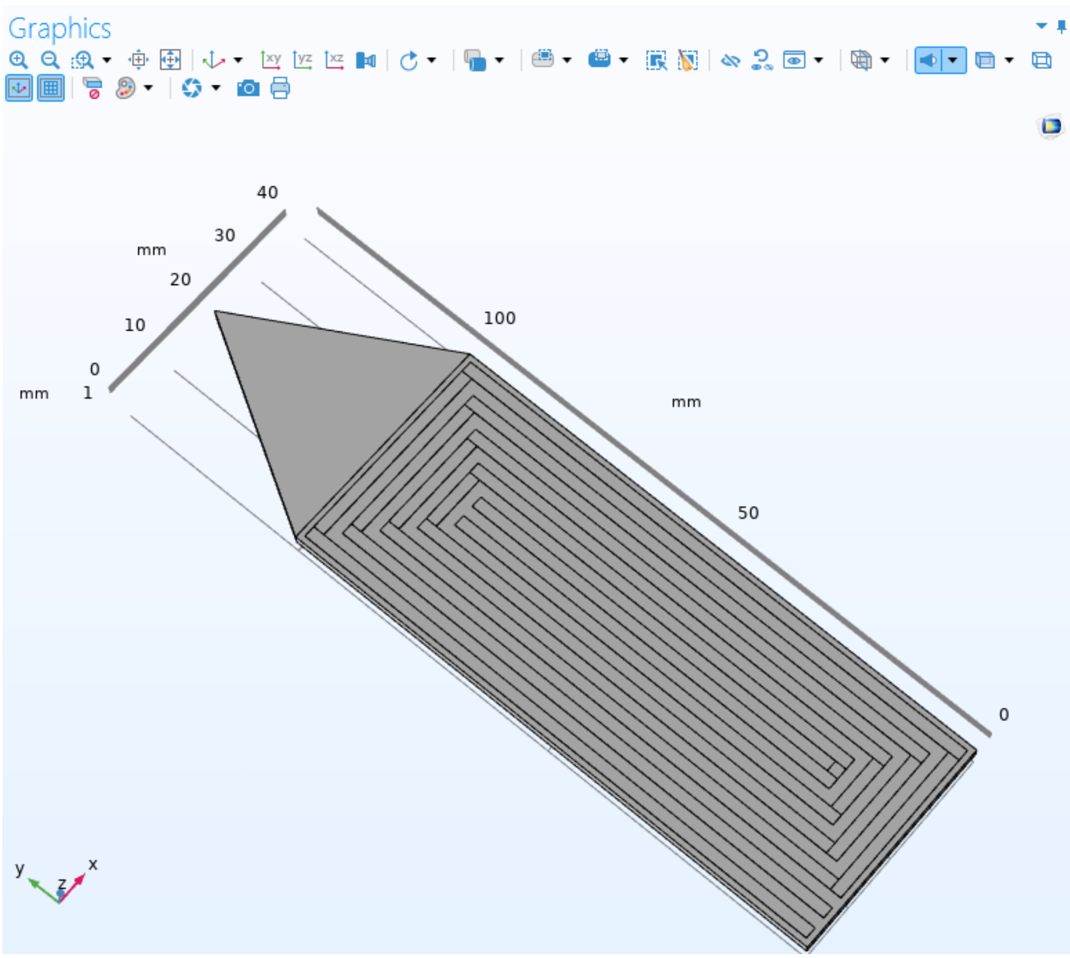


Fig 3.6 Structure of Model B

The moisture sensor model is built by enclosing the entire structure within a circular hollow sphere, which serves as the encapsulating environment. This environment is crucial for accurate simulations and allows for a realistic portrayal of the sensor's behavior under varying moisture conditions. The permittivity of the hollow sphere is adjusted during the simulation phase, reflecting the dynamic interaction between the sensor and its environment. This allows for a level of adaptability crucial for accurately capturing the sensor's response to changing soil moisture levels. The iterative simulation process, integrating environmental enclosure and permittivity adjustments, is essential for understanding the capacitance variations of the fringing field capacitive soil moisture sensor. The ultimate goal is to refine and optimize sensor designs by understanding the impact of environmental factors on sensor performance, enhancing its applicability in precision agriculture and environmental monitoring.

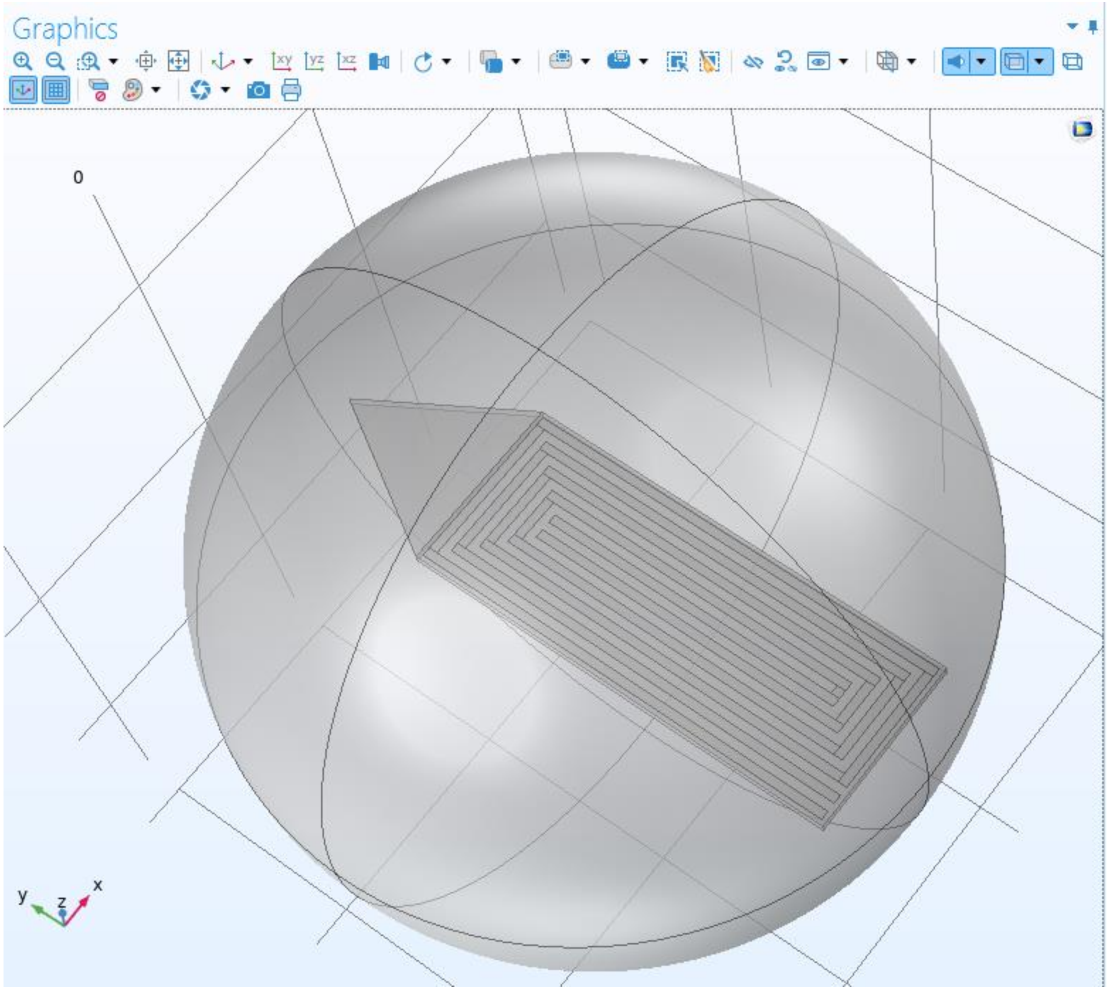


Fig 3.7 Enclosed Environment for Model B

After establishing the model's base and intricate fringing field pattern, the next step involves creating a mesh using the already defined physics. The level of the mesh is set to be extremely fine to have a precise meshed model that will yield the best possible results. In the last processing step, we define the physics of the model first and set the permittivity of the fringing pattern, which depends on the material we are using. Copper has a permittivity value of 1, aluminum has 6, and silicon has a value of 11.6[6]. Then, we define the two terminals of the sensor with charges with a value of +1C and -1C, respectively. In the final step, we start computing the model. In each iteration of computing, we change the values of permittivity of the sphere to achieve different capacitance values. After computing each iteration of the model, the final processed model is produced, which defines how the sensor reacts to different conditions. On the window in the sidebar, electric potential is shown for a better understanding of current flow and other things. This iterative simulation process, integrating the unique environmental enclosure and permittivity adjustments, is fundamental to gaining insights into the intricate capacitance variations of the fringing field capacitive soil moisture sensor. The ultimate goal is to refine and optimize sensor designs by comprehensively understanding the impact of environmental factors on sensor performance, enhancing its applicability in precision agriculture and environmental monitoring.

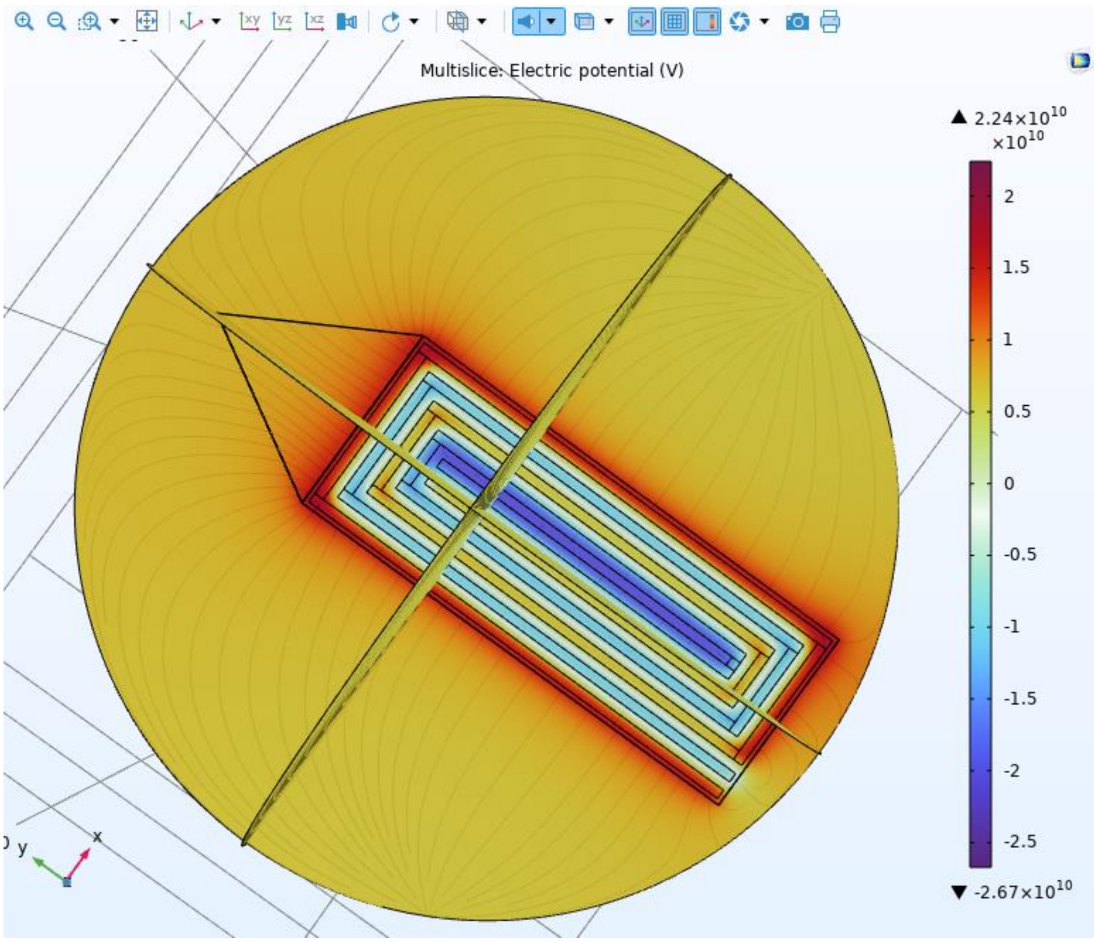


Fig 3.8 Computation of potential for Model B

3.2.3 Designing of Model C

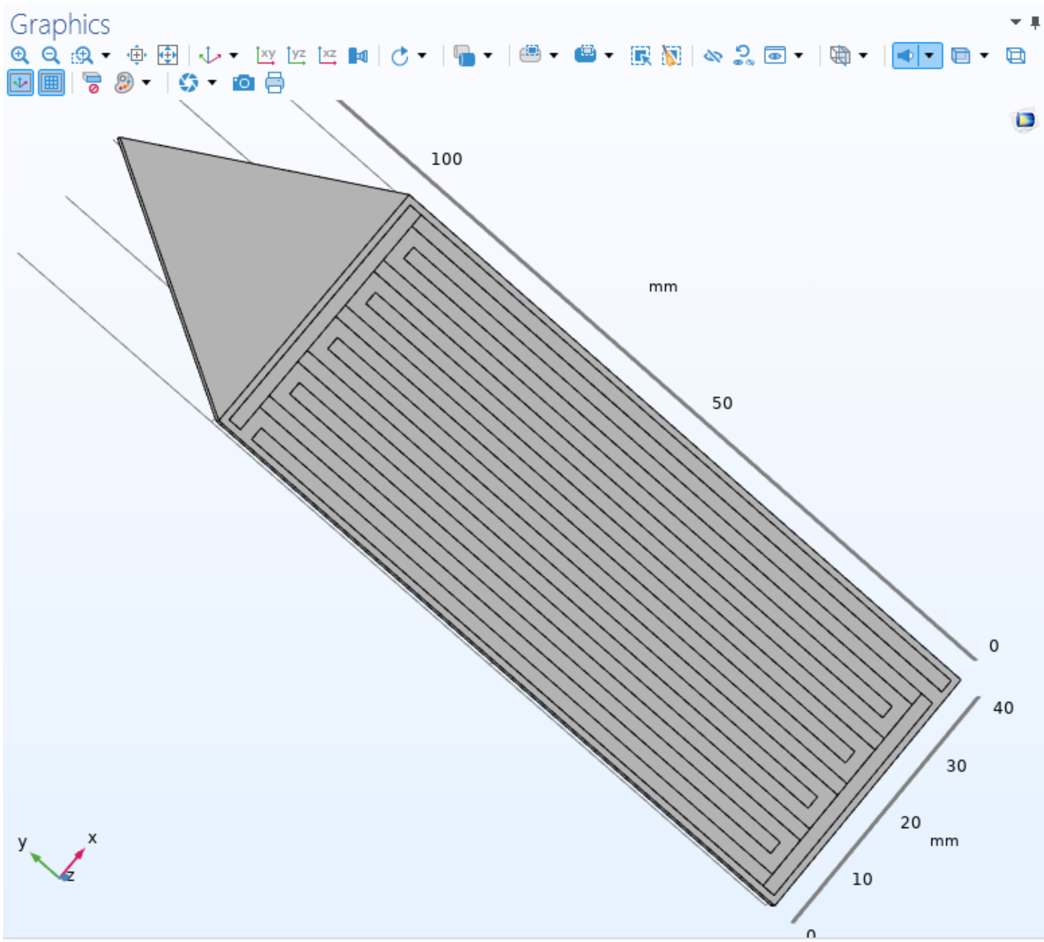


Fig 3.9 Structure of Model C

The design process for Model C, a capacitive soil moisture sensor, begins within COMSOL Multiphysics. The initial step involves creating a rectangular layout with dimensions of 100mm x 100mm and a thickness of 2mm. This forms the base for the sensor, with a particular focus on the fringing field aspect. The substrate material is crucial, and the chosen material is the FR4 board, known for its excellent electrical properties and common use in electronics. The next important step is to establish the fringing field pattern on the substrate. Using COMSOL's versatile tools, a design is created with precise dimensions for the fringing field traces, each having a thickness of 0.1mm. This complex pattern is key to the sensor's functionality, as it allows the electric field to interact with the soil, enabling accurate moisture measurements. The thickness of the fringing field traces is a parameter of interest and is systematically adjusted and optimized through iterative simulations within COMSOL. This iterative process ensures that the final design considers both material properties and geometric aspects to achieve optimal sensor performance.

Upon the completion of the base and pattern formation of the model, the next phase involves enclosing the entire structure within a hollow spherical shell. This shell is characterized as a blank material, serving as the environmental context for the moisture sensor's operation. The sensor, now nestled within this spherical environment, is primed to perform its function of moisture detection. As we progress to the simulation stage, a critical modification is introduced - the permittivity of the hollow sphere is altered. This adjustment is not arbitrary but is a calculated move to influence the capacitance value of the sensor. The permittivity of the sphere, which essentially quantifies the ability of a material to store electrical energy in an electric field, directly impacts the capacitance. As the permittivity fluctuates, so does the capacitance, leading to varied sensor readings. These changes in the capacitance value are meticulously recorded, providing valuable insights into the sensor's performance under different environmental conditions. This iterative process of permittivity adjustment and capacitance measurement forms the crux of the simulation stage, ultimately yielding the desired results. In essence, the model's design, coupled with the strategic manipulation of environmental conditions, paves the way for an in-depth understanding of the sensor's behaviour, thereby contributing to the optimization of its moisture detection capabilities.

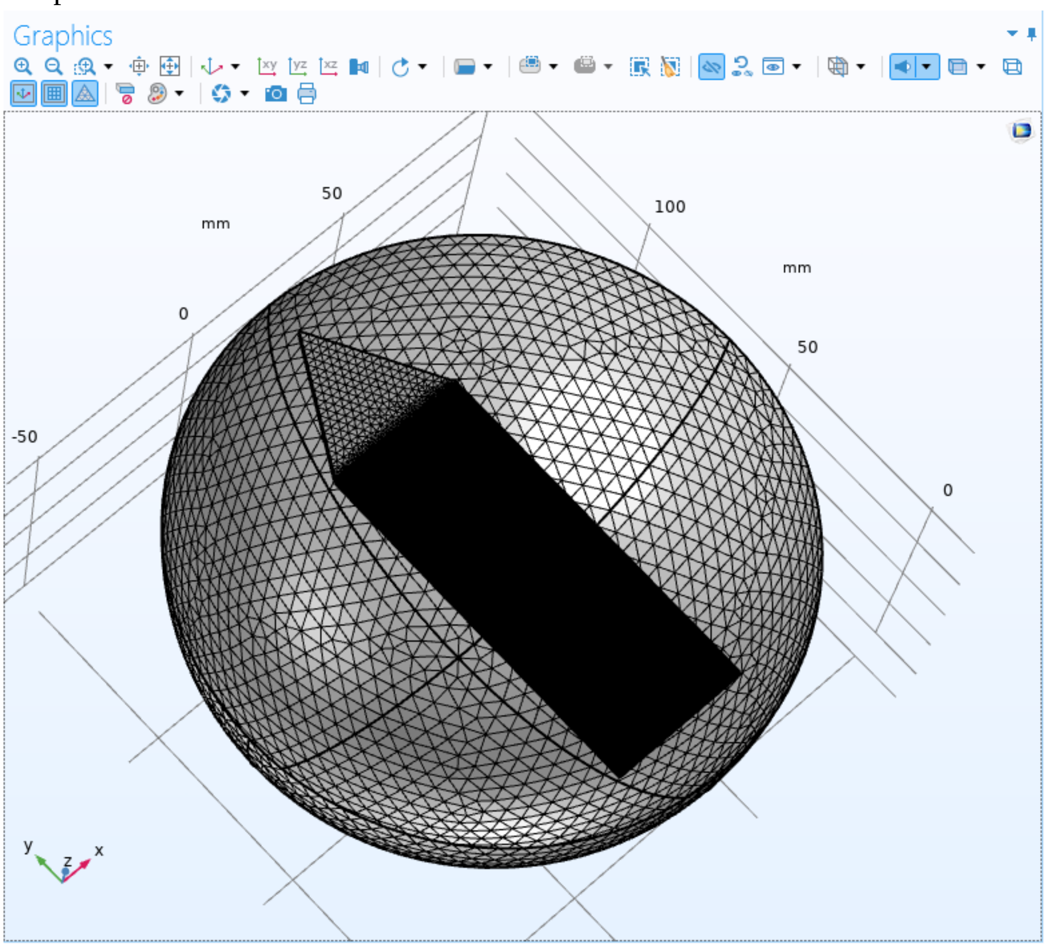


Fig 3.10 Mesh of Model C

Following the design and simulation stages, we transition to the initial phase of the computation process. Here, we construct a mesh, a crucial step that involves the discretization of the model's geometry into smaller, manageable units. This mesh is created based on the physics already defined in the model. To ensure precision and accuracy in the results, we set the mesh level to be extremely fine. This fine meshing allows for a detailed representation of the model, capturing even the minutest variations in the geometry. Consequently, this leads to more accurate computations and, ultimately, the best possible results.

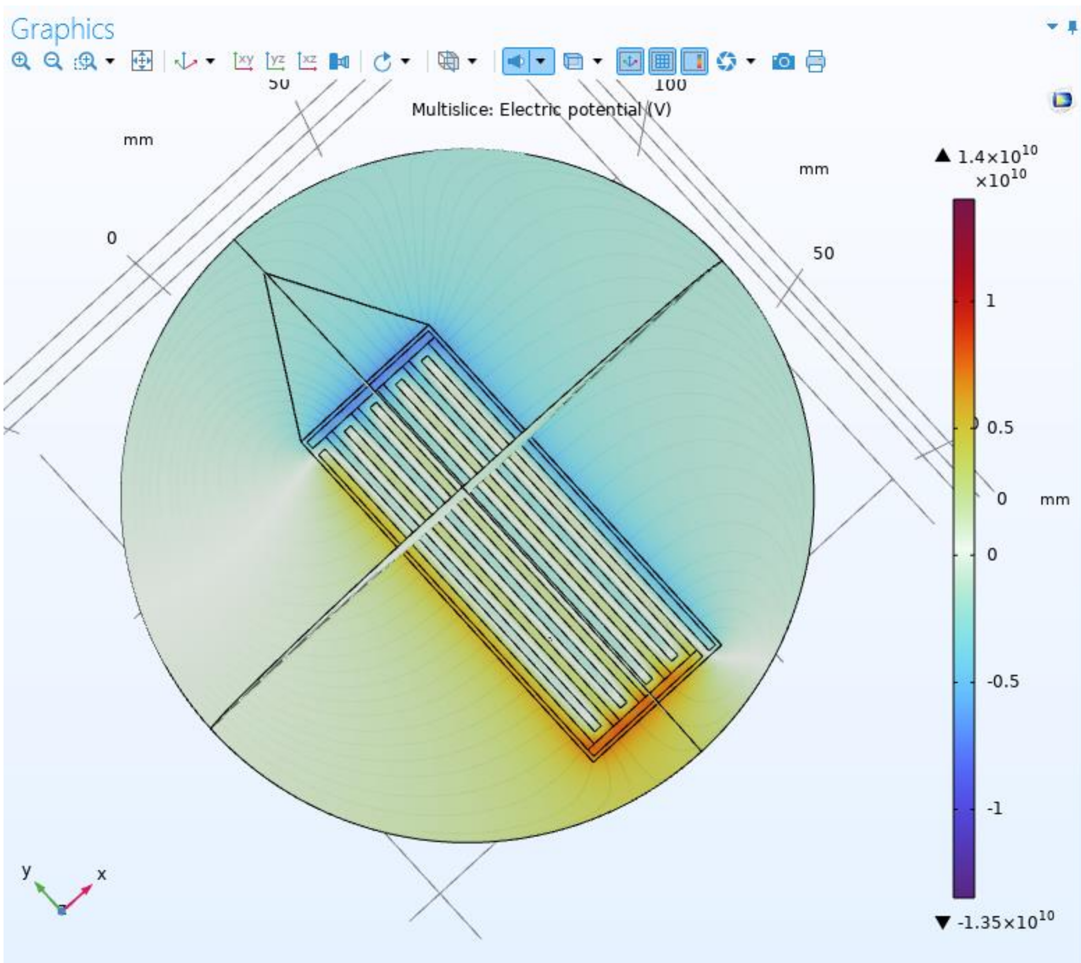


Fig 3.11 Computation of potential for Model C

The final processing step in the development of our capacitive soil moisture sensor model involves defining the physics of the model and setting the permittivity of the fringing pattern. The permittivity, a measure of how an electric field affects and is affected by a dielectric medium, is dependent on the material used in the fringing pattern. In our model, we explore three materials - copper, aluminum, and silicon, each with distinct permittivity values. These values are critical as they influence the electric field distribution and, consequently, the sensor's capacitance response to changes in soil moisture.

Following the definition of permittivity, we proceed to define the two terminals of the sensor, assigning them charges of +1C and -1C respectively. With the physics defined and the charges assigned, we commence the computation of the model. This computation is not a one-time process but an iterative one. In each iteration, we alter the permittivity of the sphere, a move that directly impacts the capacitance value. As the permittivity changes, so does the capacitance, leading to varied sensor readings. To aid in the understanding of the current flow and other aspects of the sensor's operation, the electric potential is displayed on a sidebar window. It allows us to observe the electric field distribution and the changes in capacitance, thereby contributing to the optimization of the sensor's design and functionality.

3.2.4 Sensor Fabrication

The fabrication of the capacitive soil moisture sensor was executed using cost-effective PCB technology, which is well-suited for creating the interpenetrating comb pattern required for fringe capacitance measurements. The process began with selecting an FR4 board with specific dimensions of 100mm x 20mm. This board size was chosen to accommodate the sensor's design, which included a 0.90 mm gap between adjacent electrodes and a width of 2 mm for each electrode plate. The FR4 board was first cut to size and then thoroughly cleaned with isopropyl alcohol to ensure a contaminant-free surface, crucial for the subsequent steps. Next, the circuit design, featuring the interpenetrating comb pattern, was printed on glossy photo paper using a laser printer. The choice of glossy photo paper is essential as it allows for precise toner transfer. The printed photo paper was positioned on the FR4 board, and a small amount of acetone was applied to lightly moisten the paper. This step aids in the toner transfer process by making the toner more adhesive to the board surface. An iron was then used to apply even heat and pressure to the board for 10-15 minutes. This process ensured that the toner from the printed design adhered firmly to the FR4 board.

After ironing, the board was soaked in warm water to facilitate the removal of the photo paper. The paper was carefully peeled off, leaving the toner design transferred onto the FR4 board. This transfer process was inspected to ensure that the toner design accurately represented the intended sensor pattern. The next step involved etching the board in a ferric chloride solution. The board was submerged in the etching solution for several hours, with occasional agitation to promote uniform etching. Ferric chloride is a common etchant for copper and effectively removes the exposed copper, leaving behind the desired sensor pattern protected by the toner. Once the etching process was complete, the board was thoroughly rinsed to remove any residual ferric chloride. The remaining toner was then removed using acetone, revealing the clean copper traces of the interpenetrating comb pattern. The resulting sensor pattern was inspected to ensure that it matched the design specifications, with a focus on the integrity and precision of the electrode gaps and widths.

The final sensor featured an interpenetrating comb pattern with a fringe capacitance design. The specific dimensions and layout of the electrodes were critical in achieving the desired capacitive response. The 0.90 mm gap between electrodes and the 2 mm width of each electrode plate were optimized to enhance the sensor's sensitivity to soil moisture variations. This configuration allowed for effective interaction with the surrounding soil, where changes in moisture content resulted in detectable variations in capacitance.

Overall, the PCB-based fabrication method proved to be an efficient and cost-effective approach for creating the capacitive soil moisture sensor. The detailed steps ensured that the sensor was manufactured with high precision, meeting the design criteria necessary for accurate soil moisture measurement. The use of standard materials and techniques facilitated the production process, making it feasible for both small-scale and larger production runs. The resulting sensor was ready for integration into the circuit design phase, where it would be combined with an ATmega328 microcontroller and a Bluetooth module for real-time soil moisture monitoring.

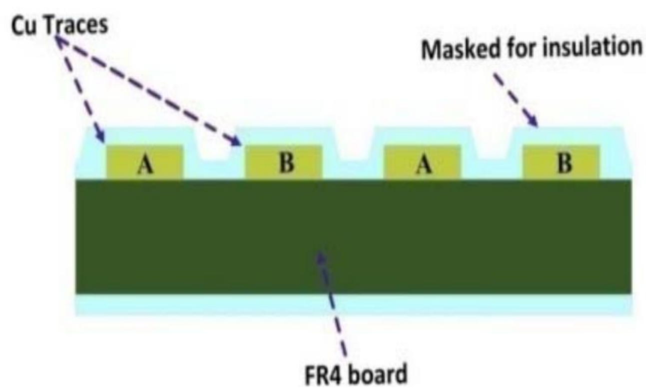


Fig 3.12 Sensor Fabrication **Fig 3.13** 2-D illustration of sensor configuration

3.2.5 Electronics Interfacing Circuit

Arduino Pro Mini 5V

The Arduino Pro Mini 5V is a compact, versatile microcontroller board based on the ATmega328 microcontroller. Operating at 5 volts, it is designed for projects where space and power efficiency are critical. The Pro Mini offers 14 digital input/output pins, 6 of which can be used as PWM outputs, and 8 analog inputs, providing ample connectivity for various sensors and modules. It features a 16 MHz clock speed, ensuring reliable and quick processing of data. Due to its small size, it lacks a USB port, so an external FTDI board or USB-to-serial adapter is needed for programming. The Pro Mini is ideal for embedded systems and wearable electronics, offering the full functionality of larger Arduino boards in a more compact form factor. In this project, it acts as the central processing unit, reading data from soil moisture sensors, processing it, and controlling data transmission and display.

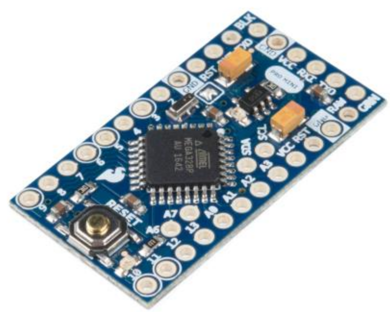


Fig 3.14 Arduino Pro mini

Bluetooth Module (HC-05)

The HC-05 Bluetooth Module is a popular wireless communication module used to add Bluetooth capabilities to projects. It supports both master and slave modes, making it versatile for various applications. The module operates at 3.3V but is 5V tolerant on its input pins, which allows it to interface seamlessly with the 5V Arduino Pro Mini. The HC-05 uses serial communication (UART), typically connected to the TX and RX pins of the microcontroller. It features an onboard LED to indicate connection status, a key pin for entering AT command mode, and a range of up to 10 meters. The HC-05 enables the sensor system to transmit soil moisture data wirelessly to a smartphone or computer, facilitating remote monitoring and control. This eliminates the need for physical connections, enhancing the convenience and flexibility of the sensor system.

Fig 3.15 Bluetooth Module

OLED Display (0.96 inch, 4P)

The 0.96-inch OLED Display is a small, high-contrast screen used for real-time data visualization. It features a resolution of 128x64 pixels, providing clear and sharp display output. The display operates on I2C communication, utilizing only two pins (SDA and SCL) for data transmission, which simplifies the wiring and leaves more pins available on the Arduino Pro Mini for other uses. It operates at low power, making it suitable for battery-powered projects. The OLED display can show various types of information, such as numerical values, graphs, and text, making it versatile for different applications. In this project, it displays real-time capacitance values from the soil moisture sensors, allowing users to quickly assess soil moisture levels without needing additional devices. Its small size and low power consumption make it an excellent choice for compact and portable sensor systems.

Fig 3.16 OLED Display

Push Button

The Push Button is a simple yet crucial component for user interaction within the circuit. It is a momentary switch that completes an electrical circuit when pressed, sending a signal to the Arduino Pro Mini. This signal can be programmed to trigger various functions, such as resetting the system, calibrating the sensors, or initiating data transmission. The push button is typically connected to a digital input pin on the microcontroller, with a pull-down resistor to ensure a stable LOW state when the button is not pressed. When the button is pressed, the input pin reads HIGH, allowing the microcontroller to detect the press. In this project, the push button enhances user control and flexibility, enabling manual overrides and adjustments. It provides a simple interface for the user to interact with the system without needing additional hardware or software interfaces, contributing to the overall usability of the soil moisture sensor system.

Fig 3.17 Push Button

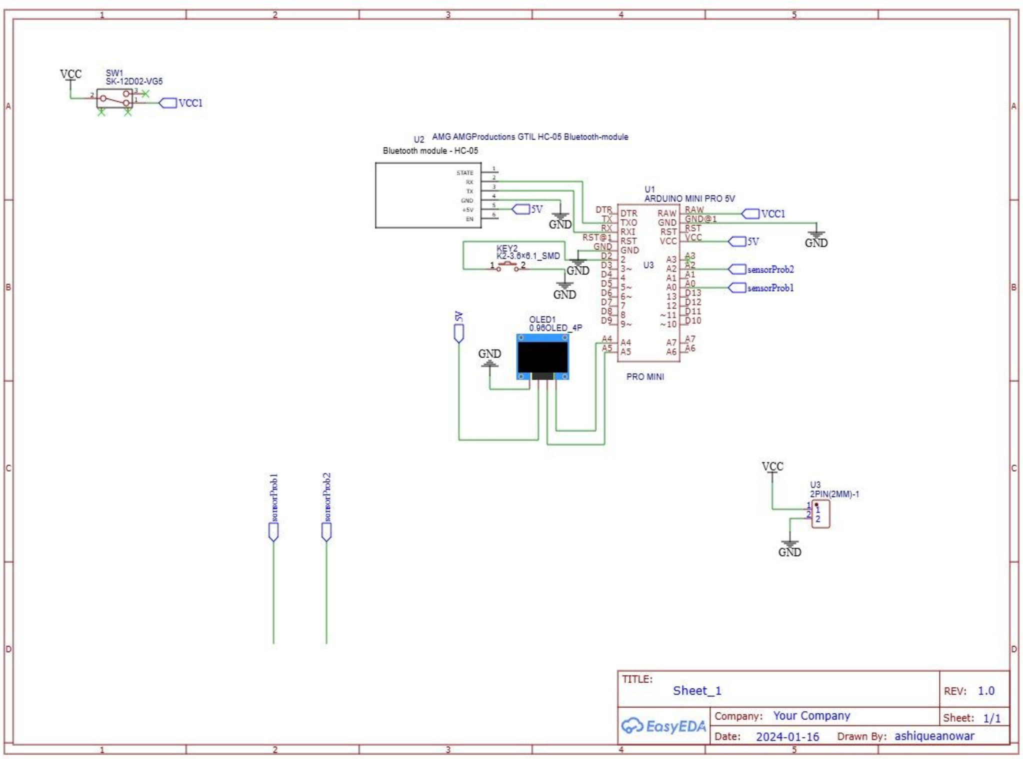


Fig 3.18 Schematic Circuit Diagram

The Arduino Pro Mini serves as the central processing unit of the circuit, orchestrating the measurement, processing, and transmission of soil moisture data. The sensor probes are connected to the analog input pins A2 and A0 of the Arduino Pro Mini. These probes function by detecting changes in soil capacitance, which varies with moisture levels. The capacitance works on the principle of the time constant(T), defined as the time it takes for the voltage across the capacitor to reach 63.2% of its fully charged voltage. Knowing the internal resistance(R) of the Arduino Pro Mini and taking into account the time constant, the capacitance(C) can be calculated using the equation : $T = R*C$. The capacitance changes are converted into analog signals, which are then read by the microcontroller. The ATmega328 microcontroller on the Arduino Pro Mini processes these analog signals to determine the soil moisture content, converting the raw capacitance data into meaningful moisture readings.

The ATmega328 microcontroller is a valuable component in this circuit due to its versatile capabilities and efficient performance. With its 16 MHz clock speed and ample input/output pins, it can handle multiple sensors and modules simultaneously, making it ideal for complex sensor networks like this one. Its low power consumption also ensures that the sensor system can operate efficiently, even in battery-powered applications. The ATmega328's ability to execute intricate algorithms and manage real-time data processing is crucial for accurately interpreting the analog signals from the soil moisture sensors. The processed data from the microcontroller is then sent to the OLED display for real-time monitoring. The OLED display, connected to the Arduino via I2C communication on pins A4 (SDA) and A5 (SCL), allows users to view the current soil moisture levels directly on the device. The use of I2C communication is advantageous because it simplifies the wiring by using only two pins, leaving other pins available for additional components or sensors. The display updates continuously to reflect real-time changes in soil moisture, providing immediate feedback to the user.

Simultaneously, the processed data is transmitted to the Bluetooth module (HC-05) for wireless communication. The Bluetooth module is connected to the Arduino's serial communication pins, with the TX pin of the Bluetooth module connected to the RX pin of the Arduino (D0), and the RX pin of the Bluetooth module connected to the TX pin of the Arduino (D1). This setup allows for bidirectional data transmission between the microcontroller and the Bluetooth module. The HC-05 module is responsible for wirelessly transmitting the soil moisture data to a paired smartphone or computer. The Bluetooth module's ability to operate in both master and slave modes makes it versatile for different communication needs. It ensures that the data collected by the sensor system can be monitored remotely in real-time, enhancing the system's flexibility and user convenience.

The power supply connections ensure that all components receive the appropriate voltage levels for optimal operation. The Arduino Pro Mini, operating at 5V, provides the necessary power to the sensor probes, OLED display, and Bluetooth module. The integration of a stable power supply is critical to maintain the accuracy and reliability of the sensor readings. Any fluctuations in power can lead to erroneous data, so a well-regulated power supply is essential for the system's overall performance. Additionally, the push button (KEY1) is integrated into the circuit to provide user interaction. The push button is connected to a digital input pin on the Arduino, allowing it to trigger specific functions when pressed. These functions could include resetting the system, initiating a recalibration of the sensors, or triggering a manual data transmission cycle. The inclusion of the push button enhances the system's usability, allowing the user to interact with the sensor system without needing to connect additional hardware or use software interfaces.In summary, the soil moisture sensor system integrates various components to achieve efficient measurement, processing, and transmission of soil moisture data.

CHAPTER 4

RESULT ANALYSIS

4.1 Introduction

The result analysis of our capacitive soil moisture sensor project is a critical phase that validates the effectiveness and accuracy of the sensor design and implementation. In the first phase, we employed COMSOL Multiphysics for finite element analysis, simulating various sensor models with copper, silicon, and aluminum traces to identify the optimal configuration. This simulation helped us understand the relationship between soil permittivity and capacitance, ultimately guiding us to the most promising sensor design with a honeycomb-like fringing field pattern. In the second phase, we fabricated this design using PCB technology, ensuring precise electrode dimensions and spacing. The fabricated sensors were then integrated into a circuit with an Arduino Pro Mini, OLED display, and Bluetooth module for real-time data acquisition and wireless transmission. We conducted extensive testing using the gravimetric method and observed the sensor's performance across different soil types. Our result analysis focuses on comparing the sensor's output with established methods and previous studies, highlighting its accuracy, reliability, and potential for improving irrigation practices. The findings from our tests show a high correlation coefficient, indicating the sensor's efficacy in providing precise soil moisture readings, thereby supporting sustainable agricultural practices.

4.2 Results - Phase 1

We meticulously collected and organized data in tables featuring critical parameters for our analysis of capacitive soil moisture sensor models (Model A, Model B, and Model C). The tables have rows titled "Material," "Material Permittivity," "Permittivity of Soil," "Charge Q1," "Charge Q2," "Potential V1," "Potential V2," "Capacitance (pF) C=dQ/dV," as well as "Thickness." These tables serve as the foundation for our graphical representations, which show the "Permittivity of Soil" along the x-axis and the "Capacitance (pF) C=dQ/dV"[1] along the y-axis. Each graph corresponds to a different model, allowing us to identify trends and variations in the relationship between soil permittivity and capacitance for various materials. This visual representation allows for a thorough understanding of how each model responds to changes in soil moisture levels, with a focus on the effect of material selection on sensor performance. The following analysis will delve into the specific insights gleaned from these graphs, shedding light on the complex interplay between material properties and sensor behavior.

4.2.1 Data Analysis of Model A

The relative permittivity values of Copper, Aluminium and Silicon are 1, 6 and 11.6 respectively[6]. The charge differences are 2C.

Table 4.1: Change of capacitance of model A wrt permittivity for 3 different materials

Material	Permittivity of Soil	Potential V1	Potential V2	Capacitance (in pF)	r
Copper	5	2.17E+10	-2.17E+10	46.1	0.9999957906
	15	9.33E+09	-9.36E+09	107	
	30	5.09E+09	-5.12E+09	196	
	70	2.32E+09	-2.33E+09	430	
	100	1.65E+09	-1.65E+09	606	
Aluminum	5	2.01E+10	-2.01E+10	49.8	0.9997884136
	15	9.04E+09	-9.06E+09	110	
	30	5.25E+09	-5.30E+09	190	
	70	2.45E+09	-2.43E+09	410	
	100	1.64E+09	-1.65E+09	608	
Silicon	5	1.98E+10	-1.97E+10	50.6	0.9996961585
	15	8.99E+09	-8.98E+09	111	
	30	4.75E+09	-4.78E+09	210	
	70	2.30E+09	-2.30E+09	435	
	100	1.62E+09	-1.59E+09	623	

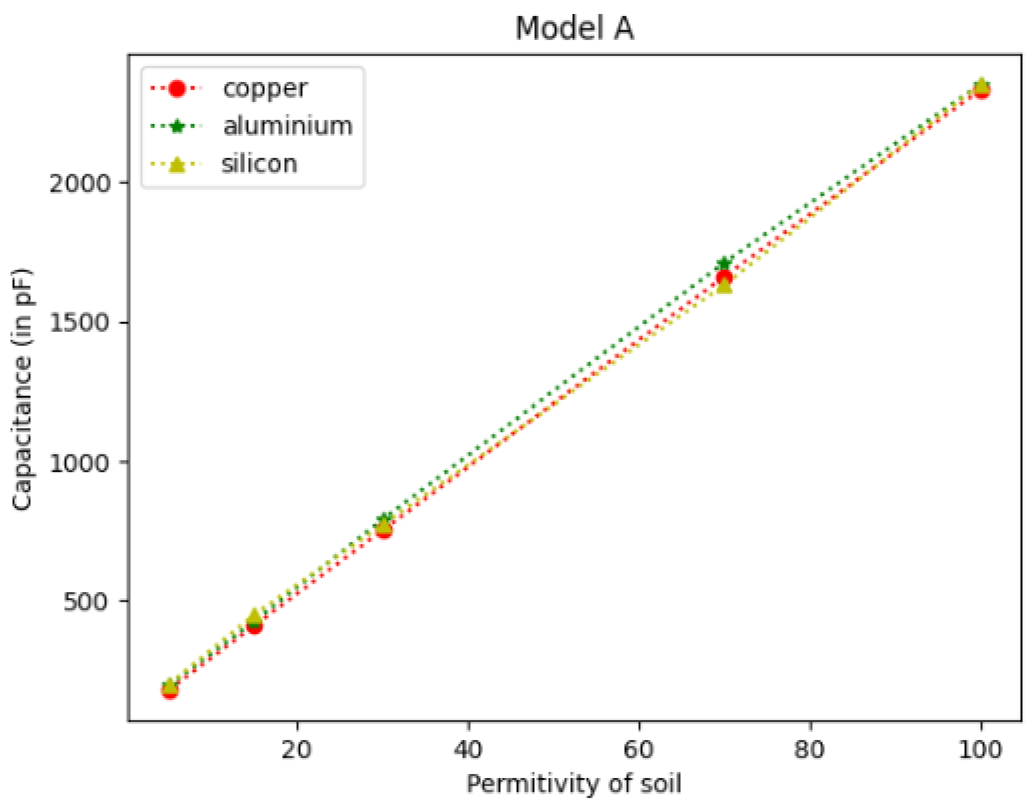


Fig 4.1 Graph of different materials of Model A

From the graph (Fig 4.1) and the table (Table 4.1) we can see that the value of the coefficient of correlation (r) is best for copper.

4.2.2 Data Analysis of Model B

The relative permittivity values of Copper, Aluminium and Silicon are 1, 6 and 11.6 respectively. The charge differences are 2C.

Table 4.2: Change of capacitance of model B wrt permittivity for 3 different materials

Material	Permittivity of Soil	Potential V1	Potential V2	Capacitance (in pF)	r
Copper	5	1.02E+10	-1.28E+10	87.0E	0.9999902652
	15	4.23E+09	-5.36E+09	209	
	30	2.25E+09	-2.90E+09	388	
	70	1.00E+09	-1.30E+09	870	

	100	7.06E+08	-9.27E+08	1220	
Aluminium	5	9.00E+09	-1.11E+09	198	0.9992020436
	15	4.03E+09	-5.07E+09	220	
	30	2.50E+09	-3.05E+09	360	
	70	9.91E+08	-1.29E+09	877	
	100	7.02E+08	-9.18E+08	1230	
Silicon	5	8.80E+09	-1.08E+10	102	0.9997513624
	15	3.98E+09	-4.98E+09	223	
	30	2.19E+09	-2.78E+09	402	
	70	9.40E+08	-1.21E+09	930	
	100	7.01E+08	-9.13E+08	1240	

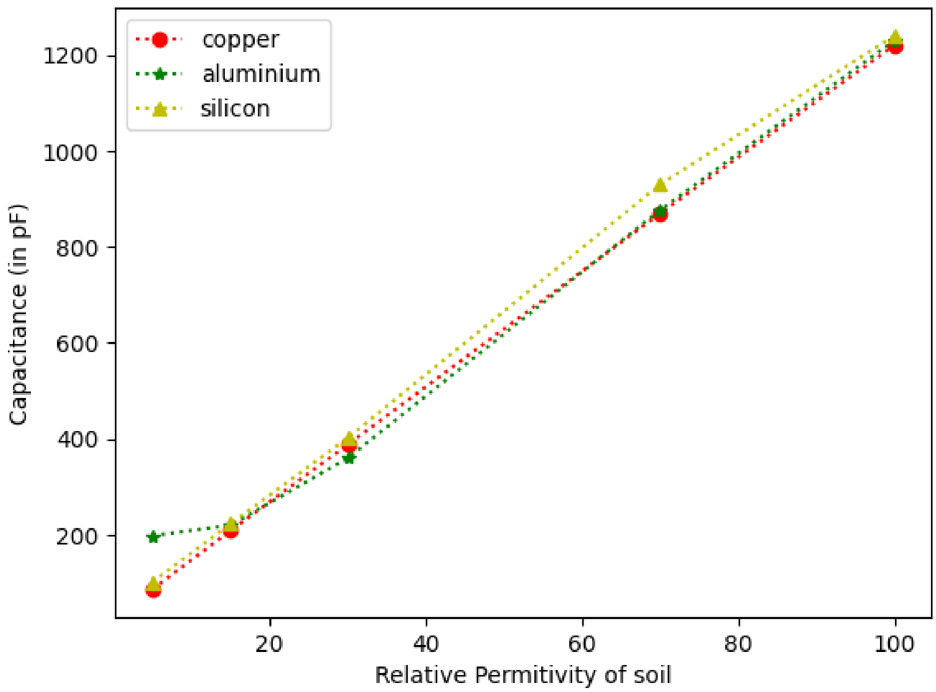


Fig 4.2 Graph of different materials of Model B

From the graph (Fig 4.2) and the table (Table 4.2) we can see that the value of the coefficient of correlation (r) is best for copper as well.

4.2.3 Data Analysis of Model C

The relative permittivity values of Copper, Aluminium and Silicon are 1, 6 and 11.6 respectively. The charge differences are 2C.

Table 4.3: Change of capacitance of model C wrt permittivity for 3 different materials

Material	Permitivity of Soil	Potential V1	Potential V2	Capacitance	r
Copper	5	5.58E+09	-5.54E+09	180	0.9999936682
	15	2.44E+09	-2.43E+09	411	
	30	1.33E+09	-1.33E+09	752	
	70	6.04E+08	-6.04E+08	1660	
	100	4.29E+08	-4.29E+08	2330	
Aluminium	5	5.15E+09	-5.05E+09	196	0.9948638981
	15	2.36E+09	-2.33E+09	426	
	30	1.27E+09	-1.26E+09	791	
	70	5.85E+08	-5.85E+08	1710	
	100	4.26E+08	-4.26E+08	2350	
Silicon	5	5.08E+09	-4.94E+09	200	0.9990893146
	15	2.23E+09	-2.21E+09	450	
	30	1.30E+09	-1.29E+09	772	
	70	6.15E+08	-6.14E+08	1630	
	100	4.27E+08	-4.24E+08	2350	

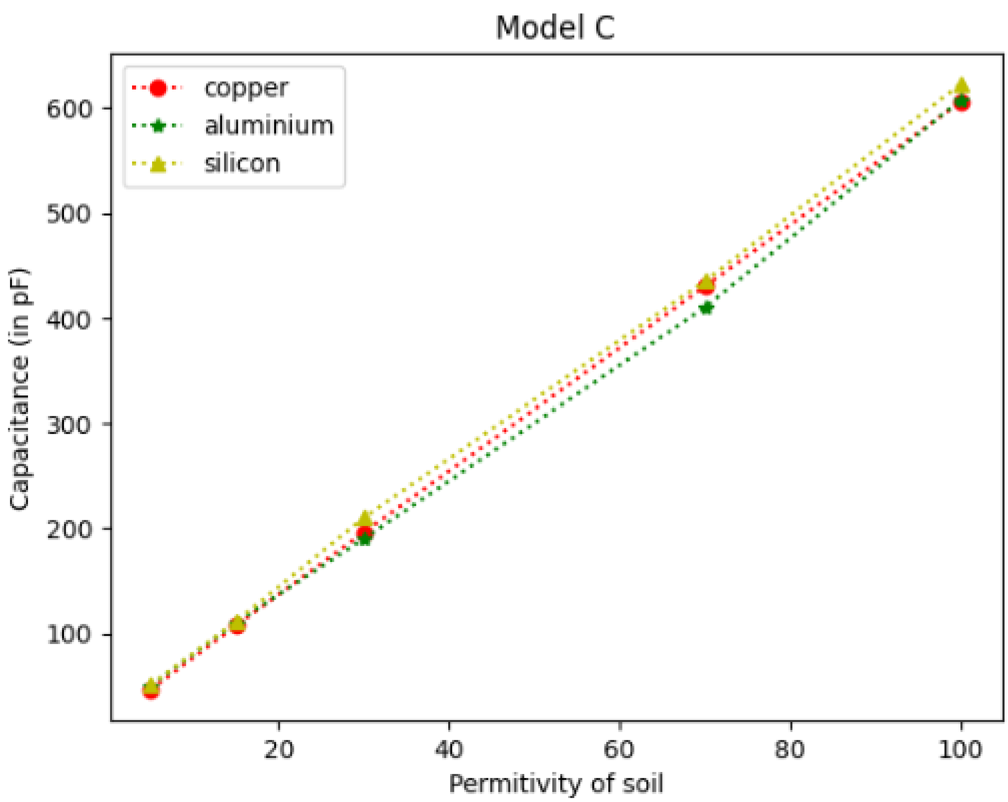


Fig 4.3 Graph of different materials of Model C

From the graph (Fig 4.3) and the table (Table 4.3) we can see that the value of the coefficient of correlation (r) is best for copper.

4.2.4 Comprehensive Analysis of Copper Across All Models

Given the discerned superiority of copper across all models in our soil moisture capacitive sensor project, a focused analysis is now directed towards the copper-based configurations. Copper emerges as the standout material, showcasing exceptional performance in terms of soil moisture sensing across various sensor models (Model A, Model B, and Model C). The inherent properties of copper, including high electrical conductivity and corrosion resistance, contribute to its effectiveness in capturing subtle changes in soil permittivity.

Table 4.4: Change of capacitance of all models wrt permittivity for copper

Model Name	Soil Permittivity value	Capacitance (in pF)	r
Model A	5	46.1	0.9999957906
	15	107	
	30	196	
	70	430	
	100	606	
Model B	5	87	0.9999902652
	15	209	
	30	388	
	70	870	
	100	1220	
Model C	5	180	0.9999936682
	15	411	
	30	752	
	70	1660	
	100	2330	

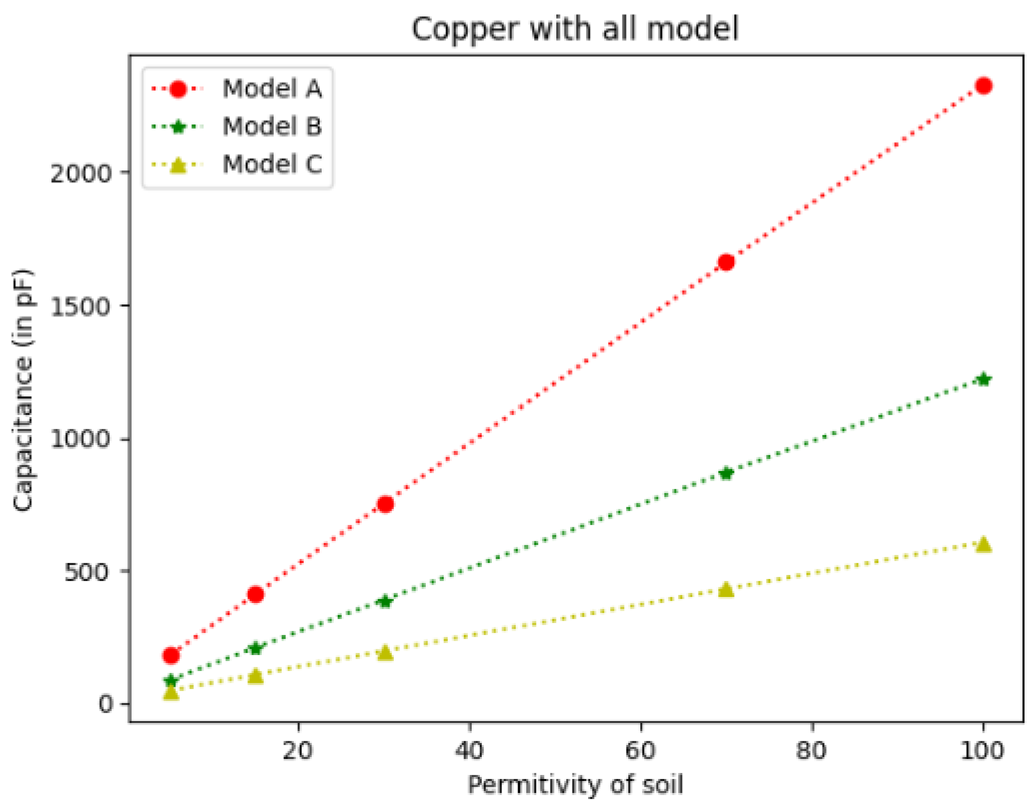


Fig 4.4 Graph of different materials of Models

The assessment of linearity, as indicated by the correlation coefficient 'r', guided the selection of the best model in our comprehensive analysis of capacitive soil moisture sensor models. **Model A** consistently had the highest 'r' value across the dataset that is nearest to 1, indicating superior linearity in its relationship between soil moisture levels and corresponding sensor readings. This compelling finding elevates Model C to the front of the pack, emphasizing its ability to provide a more precise and reliable representation of soil moisture conditions.

4.3 Results - Phase 2

The insights gained from the simulation phase (Phase 1) guided the selection of the optimal sensor design, which was subsequently fabricated in Phase 2. The COMSOL Multiphysics simulations identified the honeycomb-like fringing field pattern with the highest correlation coefficient r close to 1. This design was chosen for its superior performance in accurately correlating capacitance with soil moisture levels.

During the fabrication phase, we used PCB technology to create the interdigitated comb pattern electrodes on a 100mm x 20mm FR4 board. The electrodes had a width of 2mm and a spacing of 0.90mm, designed to maximize the fringing field effect and enhance sensitivity. The fabricated sensor was integrated into a circuit featuring an Arduino Pro Mini, OLED display, and Bluetooth module (HC-05). The sensor probes were connected to the analog input pins A0 and A2 of the Arduino Pro Mini. The microcontroller processed the analog signals, converted them into digital moisture readings, and displayed real-time values on the OLED screen via I2C communication. Additionally, the Bluetooth module, connected to the RX and TX pins, enabled wireless transmission of the processed data to a mobile application, facilitating remote monitoring and data logging.

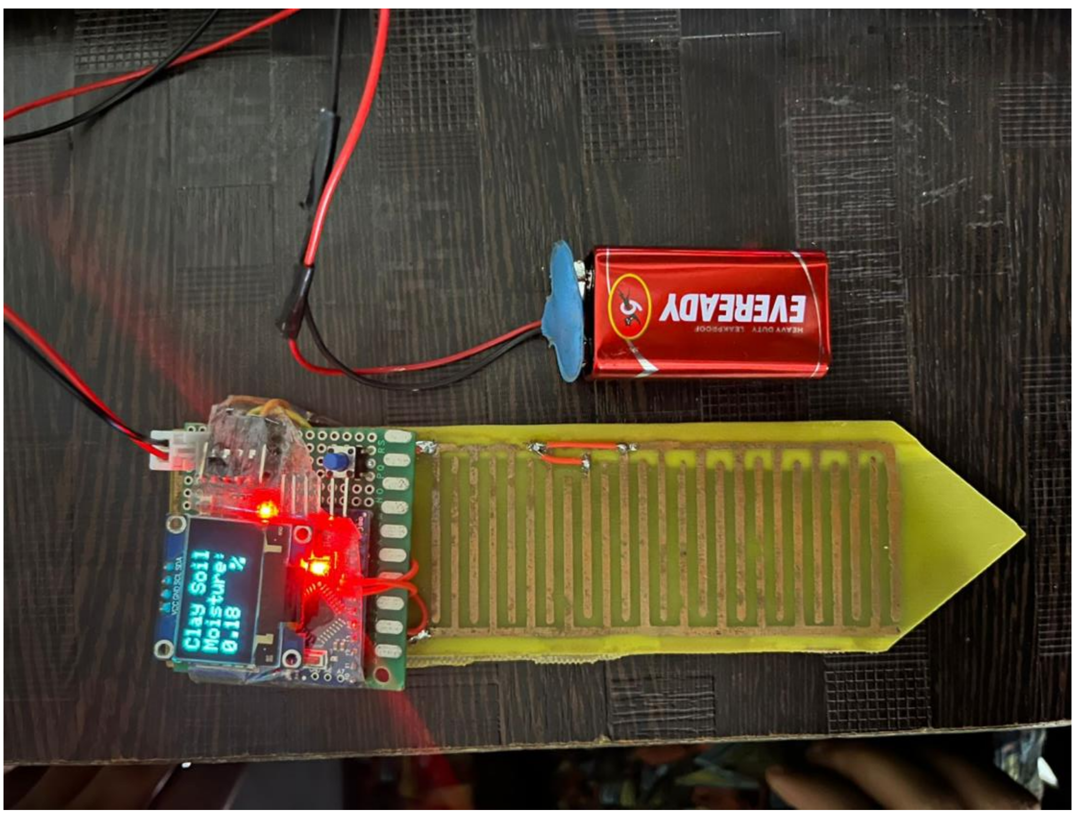


Fig 4.5 Prototype of our model

4.3.1 Gravimetric Method Calibration

Calibration is an essential step in ensuring the accuracy and reliability of our capacitive soil moisture sensor. The gravimetric method, which is widely recognized for its precision, was used for this purpose. The process begins by collecting soil samples from the three types of soil we intended to test: clay, silt, and sandy soil. Each sample is then weighed to determine its initial mass. Following this, the samples are saturated with water and left to drain for a specified period to achieve field capacity. After draining, the samples are weighed again to record the saturated mass. The samples are then placed in an oven at a controlled temperature (typically 105°C) for 24 hours to ensure complete drying. Once dried, the final mass is measured. The difference between the saturated and dry mass is used to calculate the soil moisture content. This method provides an accurate benchmark for calibrating the sensor readings.

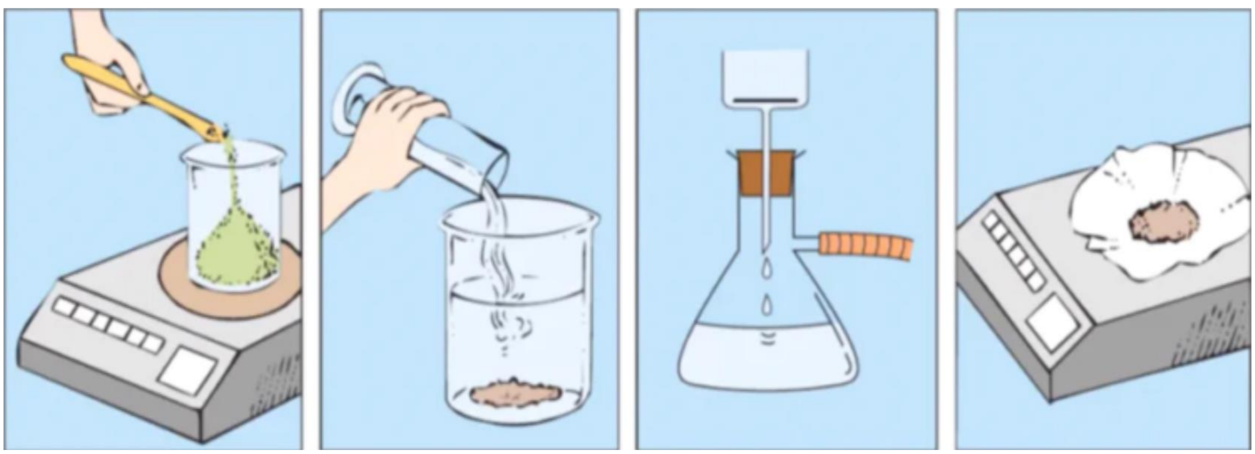


Fig 4.6 Gravimetric Method

4.3.2 Graphical Analysis of Soil Types

The calibration results for the three soil types—clay, silt, and sandy soil—were plotted to establish the relationship between soil moisture content and capacitance. The x-axis represents capacitance, while the y-axis represents the moisture content in percentage.

Clay Soil: The graph for clay soil shows a linear relationship with the equation y = 0.3506x+2.8587 and a coefficient of determination R^2 = 0.9982. This high R^2 value indicates an excellent fit, meaning the sensor's capacitance readings are highly correlated with the moisture content. The slope of 0.3506 suggests that for every unit increase in capacitance, the moisture content increases by 0.3506%, plus a small offset of 2.8587%

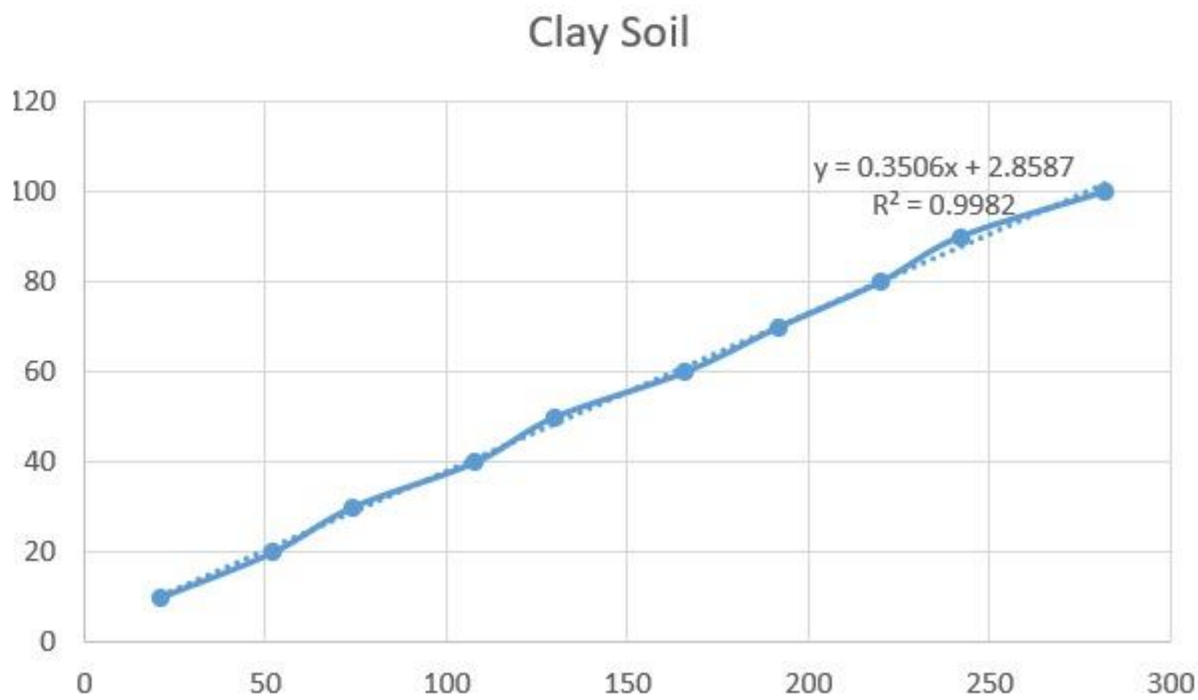


Fig 4.7 Graph for Clay Soil

Silt Soil: Similarly, the graph for silt soil also shows a strong linear relationship with the equation y = 0.3523x+3.8804 and an R^2=0.9986. The slope here is slightly higher at 0.3523, indicating a slightly greater increase in moisture content per unit capacitance compared to clay soil. The offset value is also slightly higher at 3.8804%, reflecting the inherent characteristics of silt soil.

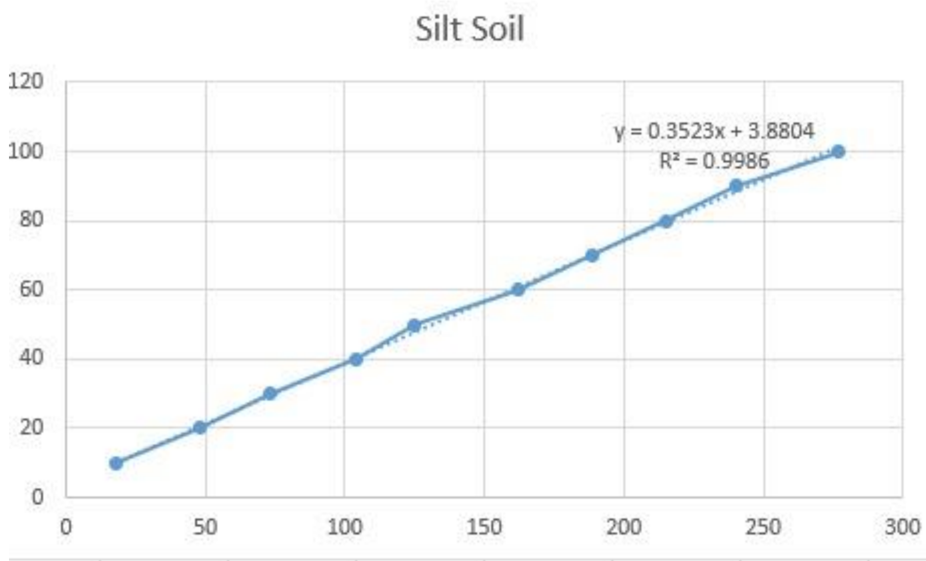


Fig 4.8 Graph for Silt Soil

Sandy Soil: The graph for sandy soil follows the same trend with the equation y=0.3552x+5.4075 and an R^2=0.9981. The slope of 0.3552 indicates the highest sensitivity among the three soil types, showing the greatest increase in moisture content per unit capacitance. The offset of 5.4075% is also the highest, which can be attributed to the lower water-holding capacity of sandy soil.

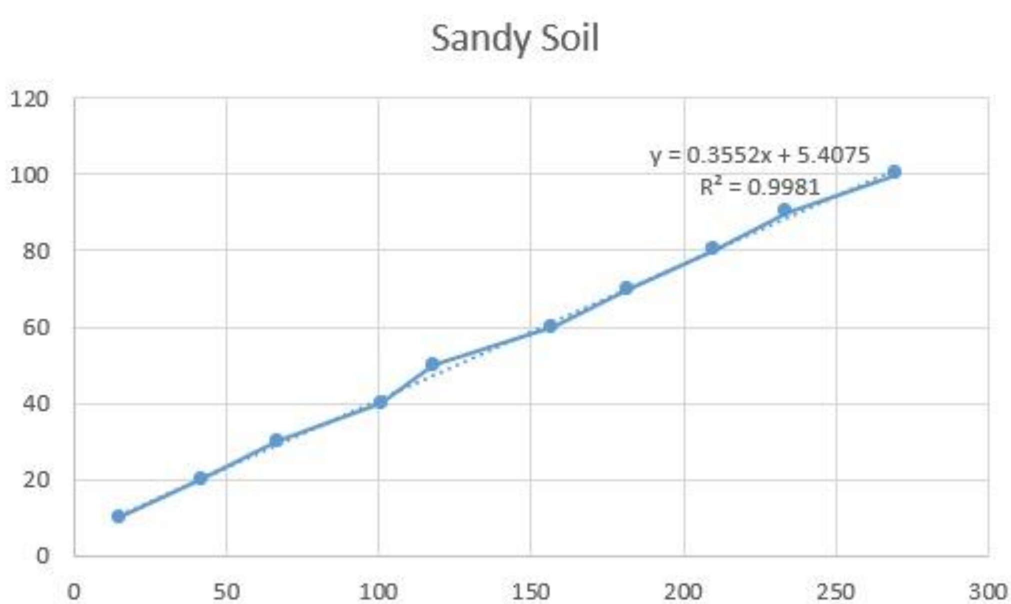


Fig 4.9 Graph for Sandy Soil

4.3.3 Comparative Analysis and Deduction

From the graphs, several key points can be deduced:

1. **Linear Relationship:** All three soil types exhibit a strong linear relationship between capacitance and moisture content, as indicated by the high R^2 values. This consistency validates the reliability of our sensor across different soil types.
2. **Sensitivity:** The sensitivity of the sensor, represented by the slope of the equations, varies slightly between the soil types. Sandy soil shows the highest sensitivity (0.3552), followed by silt (0.3523), and clay (0.3506). This indicates that the sensor can effectively capture variations in moisture content across diverse soil compositions.
3. **Offset Values:** The offset values differ among the soil types, with sandy soil having the highest (5.4075%) and clay soil the lowest (2.8587%). These offsets reflect the intrinsic moisture retention characteristics of the soils and must be considered when interpreting sensor data.

The moisture content calculation for different soils is different. Sandy soil has less water-holding capacity while clay soil has the highest capacity.

Table 4.5: Calibrated equation of Soils

Soil Type	Equation of Moisture vs Capacitance
1. Clay Soil	moisture = 0.3506 * capacitance + 2.8587
2. Silt Soil	moisture = 0.3523 * capacitance + 3.8804
3. Sandy Soil	moisture = 0.3552 * capacitance + 5.4075

The result analysis of our capacitive soil moisture sensor project demonstrates the effectiveness of our design and fabrication process. The high correlation coefficients obtained from the gravimetric calibration validate the accuracy and reliability of our sensor across different soil types. The linear relationships between capacitance and moisture content ensure consistent performance, while the circuit integration with wireless capabilities enhances usability and convenience. This project not only advances soil moisture monitoring technology but also contributes to sustainable agricultural practices by enabling precise irrigation management.

CHAPTER 5

CONCLUSION AND

FUTURE SCOPE OF WORK

5.1 Conclusion

The development of our capacitive soil moisture sensor has been a multifaceted project, meticulously executed in two distinct phases, each building upon the insights and results of the previous stage. The journey began with Phase 1, which focused on the design and simulation of various sensor models. In this phase, three unique sensor designs were conceptualized and simulated using COMSOL Multiphysics, each incorporating different fringing patterns and materials—copper, silicon, and aluminum. The primary objective was to identify a design that offered the best linearity in capacitance response to soil moisture variations. Through rigorous simulation, the honeycomb-like structure emerged as the optimal design, demonstrating the highest correlation coefficient rrr close to 1. This design's superior performance in simulating real-world conditions laid the groundwork for the subsequent fabrication phase.

Transitioning to Phase 2, we capitalized on the insights gained from the simulation studies. The honeycomb-like structure was fabricated using PCB technology, a cost-effective method that allowed for precise creation of the interdigitated comb pattern electrodes on a 100mm x 20mm FR4 board. The fabrication process involved several steps, including cutting and cleaning the board, transferring the circuit design using toner transfer, and etching the board in ferric chloride solution. The result was a meticulously crafted sensor with copper traces that maximized the fringing field effect, essential for accurate capacitance measurement.

Following fabrication, the focus shifted to integrating the sensor into a functional circuit. The circuit design centered around the Arduino Pro Mini microcontroller, chosen for its versatility and multiple analog input pins. The sensor probes were connected to analog pins A0 and A2, enabling the microcontroller to read the analog capacitance values from the soil. The processed data was displayed in real-time on a 0.96-inch OLED screen via I2C communication, providing immediate feedback on soil moisture levels. Additionally, the inclusion of an HC-05 Bluetooth module facilitated wireless data transmission, allowing the sensor readings to be monitored remotely via a mobile application. This integration of hardware and software components resulted in a robust system capable of both local and remote soil moisture monitoring.

The calibration process, crucial for ensuring the accuracy of the sensor, was conducted using the gravimetric method. This method involved comparing the sensor's capacitance readings with precise moisture measurements obtained by weighing soil samples before and after drying. Calibration was performed for three different soil types: clay, silt, and sandy soil. The results were plotted to establish the relationship between capacitance and moisture content, yielding highly linear graphs with correlation coefficients R^2 close to 1 for all soil types. The equations derived from these graphs (e.g., $y = 0.3506x+2.8587$ for clay soil) provided a reliable means of converting capacitance readings into accurate moisture content values.

The final outcome of this project is a highly sensitive and accurate soil moisture sensor that can be deployed in various agricultural and environmental monitoring applications. The sensor's design, validated through rigorous simulation and real-world testing, ensures reliable performance across different soil types. The integration of real-time data display and wireless transmission capabilities enhances its usability, making it a valuable tool for precision irrigation and soil management practices. By enabling precise monitoring of soil moisture levels, this sensor contributes to sustainable agricultural practices, optimizing water usage and improving crop yield.

Finally, this research successfully demonstrated the creation of a capacitive soil moisture sensor, from original design and modeling to manufacturing and field testing. The iterative strategy, which used lessons from each phase to influence following phases, produced a resilient and adaptable sensor system. The project's findings emphasize the need of combining powerful modeling tools, precise manufacturing processes, and inventive circuit design to generate effective and practical solutions to real-world problems.

5.2 Challenges

In the course of developing our simulation for capacitive soil moisture sensors, we encountered few challenges that influenced the process:

1. **Limited Learning Resources for Comsol:** Due to a lack of comprehensive learning resources, navigating the complexities of Comsol, our chosen simulation platform, proved difficult. The lack of detailed tutorials and documentation hampered efficient exploration of the software's capabilities, necessitating additional time and effort to comprehend its functions. This impediment highlighted the need for more accessible and comprehensive learning materials to aid in the development of simulations.

2. **Cache Interference from Previous Simulations:** The persistence of cache data from previous simulations posed a significant challenge, resulting in inadvertent manipulation

of current simulation results. The interference was a major impediment to ensuring the accuracy and integrity of our data. Addressing this issue necessitated meticulous data management practices as well as the development of strategies to reduce the impact of cached information on subsequent simulations, emphasizing the importance of thorough data clearance procedures.

3. **Extended Simulation Time for Each Model:** The simulation process for each model proved time-consuming, posing a significant constraint on project timelines. The lengthy simulation durations hampered iterative model refinement and slowed the analysis of results. Managing and optimizing simulation times emerged as an important consideration, prompting the investigation of strategies to improve computational efficiency without jeopardizing the accuracy of our soil moisture sensor models.

4. **PCB Fabrication Challenges**: Since we opted to fabricate the PCBs ourselves, we faced numerous difficulties in achieving a perfect design. Multiple attempts were necessary to produce a functioning PCB, which consumed significant time and resources. The trial-and-error process in PCB fabrication highlighted the challenges associated with manual PCB production and the need for precision in designing and etching the boards.

5. **Microcontroller Selection Challenge**: Initially, we planned to use the ESP32 as our microcontroller. However, we soon realized that the ESP32 lacks internal capacitance, which was crucial for our sensor's functionality. This necessitated a shift to the Arduino Pro Mini, which delayed our project and required additional adjustments to our design and programming.

6. **Calibration Issues**: Before calibration, the sensor provided absurd and irrelevant values upon contact with soil, which significantly hampered our initial testing and validation phases. The values were inconsistent and did not align with expected results. This issue was rectified through a meticulous calibration process, underscoring the importance of accurate calibration in sensor development.

5.3 Future Scope of Work

1. **Implementation in IoT:** This project's capacitive soil moisture sensor has promising prospects for integration into Internet of Things (IoT) applications. The sensor can help to create smart and connected agricultural systems by interacting with IoT platforms. The sensors' real-time data can be wirelessly transmitted, allowing farmers to remotely monitor soil moisture levels. Precision agriculture is aided by this integration, which enables timely decision-making, resource optimisation, and automated control of irrigation systems based on accurate, up-to-date soil moisture information. Because of the sensor's compatibility with IoT technologies, it is a critical enabler for the advancement of smart farming practices.

2. **Farming Irrigation:** The sensor's future application in agricultural irrigation is a critical component of its potential impact. The sensor can help with precise irrigation management by focusing on optimizing water usage. Farmers can receive real-time feedback on soil moisture conditions, allowing for customized irrigation schedules that align with crop needs. This targeted approach not only saves water but also increases crop yield by maintaining optimal moisture levels. The sensor's use in farming irrigation systems is consistent with sustainable agriculture practices, providing a practical solution to water scarcity concerns while also contributing to the development of environmentally conscious farming techniques.

3. **Integration into Industrial Revolution:** This project's capacitive soil moisture sensor has potential applications beyond traditional agriculture, extending its utility into the broader context of the Industrial Revolution. The sensor's adaptability and precision make it a valuable tool for large-scale cultivation, landscaping, and horticulture industries. Its use in industrial settings has the potential to revolutionize green space management by ensuring optimal soil conditions for landscaping projects and large-scale cultivation initiatives. In the context of the ongoing industrial revolution, industries can improve efficiency, reduce resource waste, and contribute to the overall sustainability of land management practices by leveraging the sensor's capabilities. This expansion of the sensor's application scope emphasizes its versatility and relevance in sectors other than traditional agriculture.
4. **Environmental Monitoring:** The capacitive soil moisture sensor can be a crucial tool in environmental monitoring and conservation efforts. By integrating these sensors into various ecosystems, scientists and environmentalists can gather real-time data on soil moisture levels, which is essential for understanding and managing natural habitats. For instance, in forest management, maintaining optimal soil moisture is vital for the health of trees and the prevention of forest fires. Similarly, in wetlands, monitoring soil moisture can

help in conserving these critical ecosystems, ensuring they remain viable habitats for a diverse range of species. The sensors can also be deployed in urban environments to monitor green spaces, helping cities to maintain healthier parks and reduce the urban heat island effect. This application underscores the sensor's potential to contribute significantly to environmental sustainability and biodiversity conservation efforts.

5. **Research and Development in Soil Science:** The capacitive soil moisture sensor holds significant potential for advancing research and development in soil science. Researchers can use these sensors to conduct detailed studies on soil moisture dynamics, enabling a better understanding of how moisture levels vary with different soil types, climatic conditions, and agricultural practices. The high precision and real-time data capabilities of the sensors allow for in-depth analysis and modeling of soil-water interactions, which can lead to the development of improved soil management strategies. Furthermore, the sensors can be used in experimental setups to test the effectiveness of various soil amendments and irrigation techniques, providing valuable insights that can drive innovation in soil conservation and agricultural productivity. By facilitating rigorous scientific research, the sensor can play a pivotal role in developing new knowledge and technologies that enhance soil health and sustainability.

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APPENDIX

Sensor Code

```
#include <Wire.h>
#include <Adafruit_GFX.h>
#include <Adafruit_SSD1306.h>

#define SCREEN_WIDTH 128
#define SCREEN_HEIGHT 64

#define OLED_RESET -1
Adafruit_SSD1306 display(SCREEN_WIDTH, SCREEN_HEIGHT, &Wire, OLED_RESET);

const int buttonPin = 2; // Push button connected to pin 2
int buttonState = 0;
int mode = 0; // Initial mode
String soil = "Clay Soil";
float moisture = 0;

const int OUT_PIN = A2;
const int IN_PIN = A0;
const float IN_STRAY_CAP_TO_GND = 24.48;
const float IN_CAP_TO_GND  = IN_STRAY_CAP_TO_GND;
const float R_PULLUP = 34.8;
const int MAX_ADC_VALUE = 1023;

void setup() {
  pinMode(OUT_PIN, OUTPUT);  // output defaults to LOW
  pinMode(IN_PIN, OUTPUT);   // output defaults to LOW
  Serial.begin(9600);
  pinMode(buttonPin, INPUT_PULLUP); // Set pin 2 as input with internal pull-
up resistor
  display.begin(SSD1306_SWITCHCAPVCC, 0x3C); // Initialize display with I2C
address 0x3C
  display.clearDisplay();
  display.setTextColor(SSD1306_WHITE);
  display.setTextSize(2);
  display.setCursor(0, 0);
  display.display();
}
```

```
void loop() {
  // Display current mode on OLED
  buttonMode();
  // Update soil type based on mode
  if (mode == 0) {
    soil = "Clay Soil";
    ClaySoil();
  } else if (mode == 1) {
    soil = "Silt Soil";
    SiltSoil();
  } else if (mode == 2) {
    soil = "Sandy Soil";
    SandySoil();
  }
  Serial.print("Soil: ");
  Serial.println(soil);
  Serial.print("Moisture: ");
  Serial.print(moisture);
  Serial.println("%");
  while (millis() % 1000 != 0);
}

void buttonMode() {
  buttonState = digitalRead(buttonPin);

  // If button is pressed, change mode
  if (buttonState == LOW) {
    mode++;
    if (mode > 2) {
      mode = 0; // Reset mode to 0 if it exceeds 2
    }
  }
}

void ClaySoil() {
  pinMode(IN_PIN, INPUT);
  digitalWrite(OUT_PIN, HIGH);
  int val = analogRead(IN_PIN);
  digitalWrite(OUT_PIN, LOW);  //discharge Cext ready for next method
  pinMode(IN_PIN, OUTPUT); //discharge Cs ready for next method

  float capacitance = (float)val * IN_CAP_TO_GND / (float)(MAX_ADC_VALUE -
```

```
val);
  moisture = (0.3506 * capacitance + 2.8587) / 100;

  // Clear previous text
  display.clearDisplay();
  display.setCursor(0, 0);
  display.println(soil);
  display.setCursor(0, 20);
  display.println("Moisture:");
  display.setCursor(0, 40);
  if (moisture < 100) {
    display.print(moisture);
    display.setCursor(90, 40);
    display.print("%");
    display.display();
  }
  else {
    display.print("100");
    display.setCursor(90, 40);
    display.print("%");
    display.display();
  }
}

void SiltSoil() {
  pinMode(IN_PIN, INPUT);
  digitalWrite(OUT_PIN, HIGH);
  int val = analogRead(IN_PIN);
  digitalWrite(OUT_PIN, LOW);  //discharge Cext ready for next method
  pinMode(IN_PIN, OUTPUT); //discharge Cs ready for next method

  float capacitance = (float)val * IN_CAP_TO_GND / (float)(MAX_ADC_VALUE -
val);
  moisture = (0.3523 * capacitance + 3.8804) / 100;

  display.clearDisplay();
  display.setCursor(0, 0);
  display.println(soil);
  display.setCursor(0, 20);
  display.println("Moisture:");
  display.setCursor(0, 40);
  if (moisture < 100) {
    display.print(moisture);
```

```
    display.setCursor(90, 40);
    display.print("%");
    display.display();
  }
  else {
    display.print("100");
    display.setCursor(90, 40);
    display.print("%");
    display.display();
  }
}

void SandySoil() {
  pinMode(IN_PIN, INPUT);
  digitalWrite(OUT_PIN, HIGH);
  int val = analogRead(IN_PIN);
  digitalWrite(OUT_PIN, LOW);  //discharge Cext ready for next method
  pinMode(IN_PIN, OUTPUT); //discharge Cs ready for next method

  float capacitance = (float)val * IN_CAP_TO_GND / (float)(MAX_ADC_VALUE -
val);
  moisture = (0.3552 * capacitance + 5.4075) / 100;

  display.clearDisplay();
  display.setCursor(0, 0);
  display.println(soil);
  display.setCursor(0, 20);
  display.println("Moisture:");
  display.setCursor(0, 40);
  if (moisture < 100) {
    display.print(moisture);
    display.setCursor(90, 40);
    display.print("%");
    display.display();
  }
  else {
    display.print("100");
    display.setCursor(90, 40);
    display.print("%");
    display.display();
  }
}
```