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IoT Enabled Design of developed hardware for the Graphene Derivatives Based Moisture sensor and Testing under Laboratory Conditions

[1] **Neema Amish Ukani,** [2] **Dr. Shelej Khera,**[3] **Saurabh S. Chakole**
[1]Ph. D. Scholar, Lovely Professional University, Punjab,
neema.ukani@gmail.com
https://orcid.org/0000-0001-6262-9005
[2]SEEE, Lovely Professional University, Punjab,
shelej.22390@lpu.co.in
[3]Ph. D. Scholar, Lovely Professional University, Punjab,
saurabhchakole89@gmail.com

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Abstract

In this study, we created a sensor to measure soil moisture using two graphene derivatives as the sensing materials. To highlight the novelty of our work, we utilized two distinct graphene de-rivatives: graphene oxide (GO) and reduced graphene oxide (rGO), each tested at three concen-trations—0.1 mg, 1 mg, and 10 mg—dispersed in 1 ml of ethanol. These solutions were then drop-casted onto interdigitated electrodes (IDEs) on a printed circuit board (PCB). We evaluated various sensor properties such as sensitivity, selectivity, hysteresis, and stability. Experimental results indicated that for both graphene derivatives, the concentration of 1 mg/1 ml (ethanol) outperformed the other concentrations of 0.1 mg/1 ml and 10 mg/1 ml (ethanol). The sensors showed changes in capacitance in response to soil moisture levels. This change was detected using custom hardware and an oscillator circuit, allowing us to accurately measure soil moisture through the capacitance variation of the GO and rGO sensors.

Keywords: *Capacitive soil moisture sensor, multi-sensing points, IoT enabled moisture sensor, Field deployments, in-situ agriculture applications*

1. **Introduction**

In the modern era, making agriculture sustainable and enhancing agricultural cul-tivation to feed the growing population is crucial. Today, achieving excellent crop quality is as important as improving agricultural productivity. One extensively utilized technique, as described in the literature, is maintaining proper soil water content within a field to ensure crop health. Soil matrices contain water molecules, which are deter-mined by the soil water content. Soil moisture sensors are frequently used to measure this content in the field. Accurate irrigation requires maintaining the soil's water con-tent between the field's capacity and the permanent wilting point. Sensors placed in the field must be sensitive and precise to detect water molecules, considering the availa-bility of various chemicals, nutrients, and fertilizers. Additionally, given the variety of soil types used in agriculture, the sensor should be reliable and reasonably priced for farmers in developing countries.

There are several methods for measuring soil water content that have been de-scribed, and they can be used both in the lab or in the field. The gravimetric method, which is regarded as the commercial standard for measuring soil moisture, is one of the frequently used lab techniques. This method is more accurate, but the time required to obtain the results (usually 24 hours) restricts its use in field applications [5, 6]. Thus, researchers have anayzed and reported the rapid in-situ detection of soil moisture sensors using different methods such as neutron probe frequency domain reflectometry and time domain reflectometry [7, 8]. These methods are accurate in nature with a rapid response time. However, the cost of these methods is very expensive where a poor farmer cannot afford such solution. In considering this, researchers have presented heat, galvanic-based pulse-based and resistive/capacitive approaches as promising method-ologies for in-situ soil moisture monitoring. Although these technologies are affordable, but they require regular calibrations, and temperature variation impacts the sensor performance [9, 10,11].

Furthermore, in order to obtain proper hectare information, a myriad of sensors must be deployed in the field, which is an expensive operation when considering the cost of reliable soil moisture measurement systems. To address this, researchers have concentrated on producing low-cost sensor systems through the micro-fabrication technique. Micro-fabrication of sensors for agricultural applications has enabled the development of not only low-cost but also accurate and fast-responding farm sensors. The sensing film for micro-sensors used in soil moisture sensors plays a vital role in terms of sensitivity and selectivity. Researchers have investigated a variety of sensing films, including PEDOT: PSS and polyaniline polymers [12-14]. However, these poly-mers' stability prevents their usage for in-situ soil moisture sensing applications. Re-searchers have thus concentrated on various nanomaterials including graphene deriv-atives, MoS2, etc. to increase stability [15–17].

Reduced graphene oxide (rGO) and graphene oxide (GO) have been used as the graphene derivatives for this work [18–19]. Because this nanomaterial offers stability, selectivity, and sensitivity, selective graphene derivatives have been selected to other derivatives [20-22]. Studying the impact of concentration on the sensor sensing prop-erties is crucial for this aim. The published research only reports measurements with a set concentration; it does not examine how different concentrations may affect the graphene derivatives' ability to detect soil moisture. This inspired us to research the performance of various graphene derivative concentrations and their impact on soil moisture sensing properties. Finding the best concentration of graphene derivatives while taking sensitivity consideration is a further objective. As a result, in this study, we selected GO with three different concentrations: 10 mg/ 1 ml (ethanol), 1 mg/ 1 ml (ethanol), and 0.1 mg/ 1 ml (ethanol). These concentrations will henceforth be referred to as GO3, GO2, and GO1, respectively, reported in our earlier work [23]. We also selected reduced graphene oxide (rGO), which has concentrations of 0.1 mg/1 ml (ethanol), 1 mg/1 ml (ethanol), and 10 mg/1 ml (ethanol). These are labelled rGO3, rGO2, and rGO1, respectively, in the reported sections [23]. The organization of this study is as follows: first, we fabricated the interdigitated electrode (IDE)-based sensors on a printed circuit board (PCB). Additionally, the fabricated sensors are drop casted with different con-centrationof rGO and GO samples. Then, soil samples is prepared with various soil water contents and further investigated the transfer function of the fabricated sensor, including its hysteresis, selectivity, sensitivity and stability. Additionally, we have de-scribed the conceivable sensing mechanism of the constructed sensor, which uses a sensing film with a variable concentration of GO and rGO.

2. Materials and methods

2.1 GO and rGO sensor soil moisture measurement

In our earlier work [23], the fabrication procedure for the GO and rGO sensor used in this study was described. According to Fig. 1 (a), GO and rGO are drop cast onto the PCB after we first fabricate the IDEs on it. The fabricated sensor is then exposed to soil moisture content ranging from 1% to 17%. In our previous work [23]., we investigated the sensor's sensor transfer qualities, such as sensitivity, response time, accuracy, etc.Fig. 1 (b) shows the sensing film with variable concentration of rGO and GO that is drop casted on the sensor and during measurements entire surface area of the sensor is covered. Further, the with the increase in soil moisture content the sensor capacitance increases. Sensor’s change in capacitance is measured with the help of LCR meter when sensor is exposed to various soil sample ranging from 1 to 17 % which is discribed in the previous paper [23]. The change in sensor capacitance is measure by using developed oscilltor circuit that convert change in capacitanc to change in frequency (sets in developed hardware within the oscillator circuit). Change in frequency is measured by using DSO when exposed to various soil sample ranging from 1 to 17 % as depicted in Fig. 1 (c)

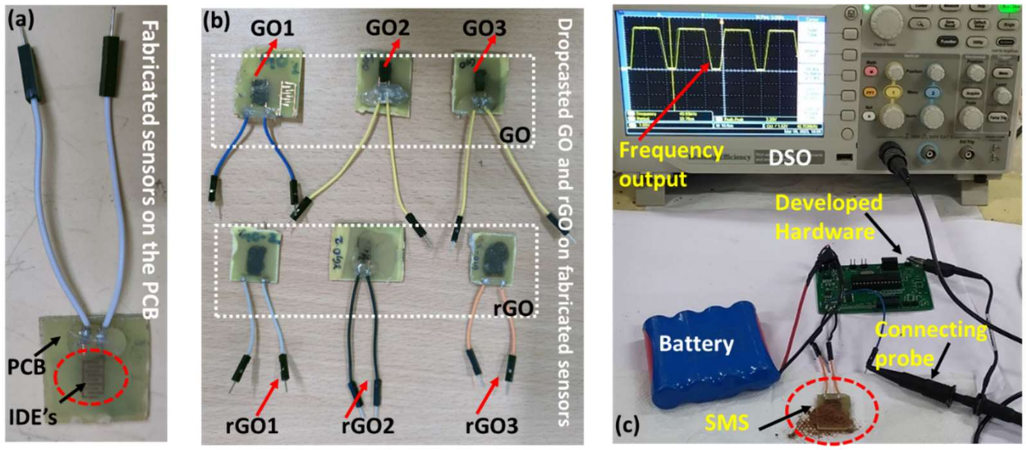


Fig. 1 (a) fabricated sensor on PCB (b) variable concentration of GO and rGO (c) experimental set-up used for the lab testing

2.2 Developed hardware

The process flow diagram for the system design and testing protocol is shown in Fig. 2(a). In order to begin this procedure, the circuit designs were divided into four major sections: the power supply voltage, the signal conditioning unit, the signal processing unit, and the sensor output and result section. Further appropriating into consideration selective distinct derivatives of the fabricated sensor (GO and rGO) using an 8:1 multiplexer delivers a capacitance to frequency converter (C to F). Furthermore, the power supply section gives electrical power to the entire system, and by connecting sensors via mux and C to F converter output given to the microcontroller which is under signal processing unit section, the values of the sensors will be sent to the server via the Wi-Fi module. Using the result and output sections, we may further store and manipulate sensor data as depicted in Fig. 2(a). Fig. 2(b) depicted block diagram of developed hardware, consist of following unit.

- Power management unit

The power supply section ensures the delivery of the necessary power to the entire system, which includes the signal conditioning unit, signal processing unit, and sensor. This unit provides the required voltage for system operation. All ICs in the proposed system operate at 3.3 V.

- Signal Conditioning Unit

The fabricated sensor's capacitance value is selected using an 8:1 multiplexer. The output from the multiplexer is then fed to a CMOS switch, which drives the value to the LMV358 C to F converter. The formula F=12.2RCF = \frac{1}{2.2RC}F=2.2RC1 is used to calculate the sensor's capacitance, which varies, and convert it to the desired frequency using the relaxation oscillator C to F. Here, RRR is the feedback resistor, CCC is the sensor's capacitance, and FFF is the measured output frequency from the C to F converter.

- Signal Processing Unit

At mega 32 microcontroller IC and 8266 Wi-Fi module comprise the components of this developed hardware. The counter port of the microcontroller receives the output of the C to F converter, and the ADC port of the microcontroller receives the analogue output of the sensors. The microcontroller reads the frequency output and analogue output and processes it, and then uploads it to the cloud with the help of an 8266 Wi-Fi module. In this work we have measured both frequency and capacitance values of the fabricated sensor and stored the data for further processing.

- Sensor

We have fabricated sensor for different derivatives of the GO and rGO i.e., GO1, GO2 and GO3 and rGO1, rGO2, rGO3 respectively. We have measured variations in sensor capacitance and frequency values that occur when fabricated sensors are exposed to different soil moisture water content ranges from (1 to 17 %).

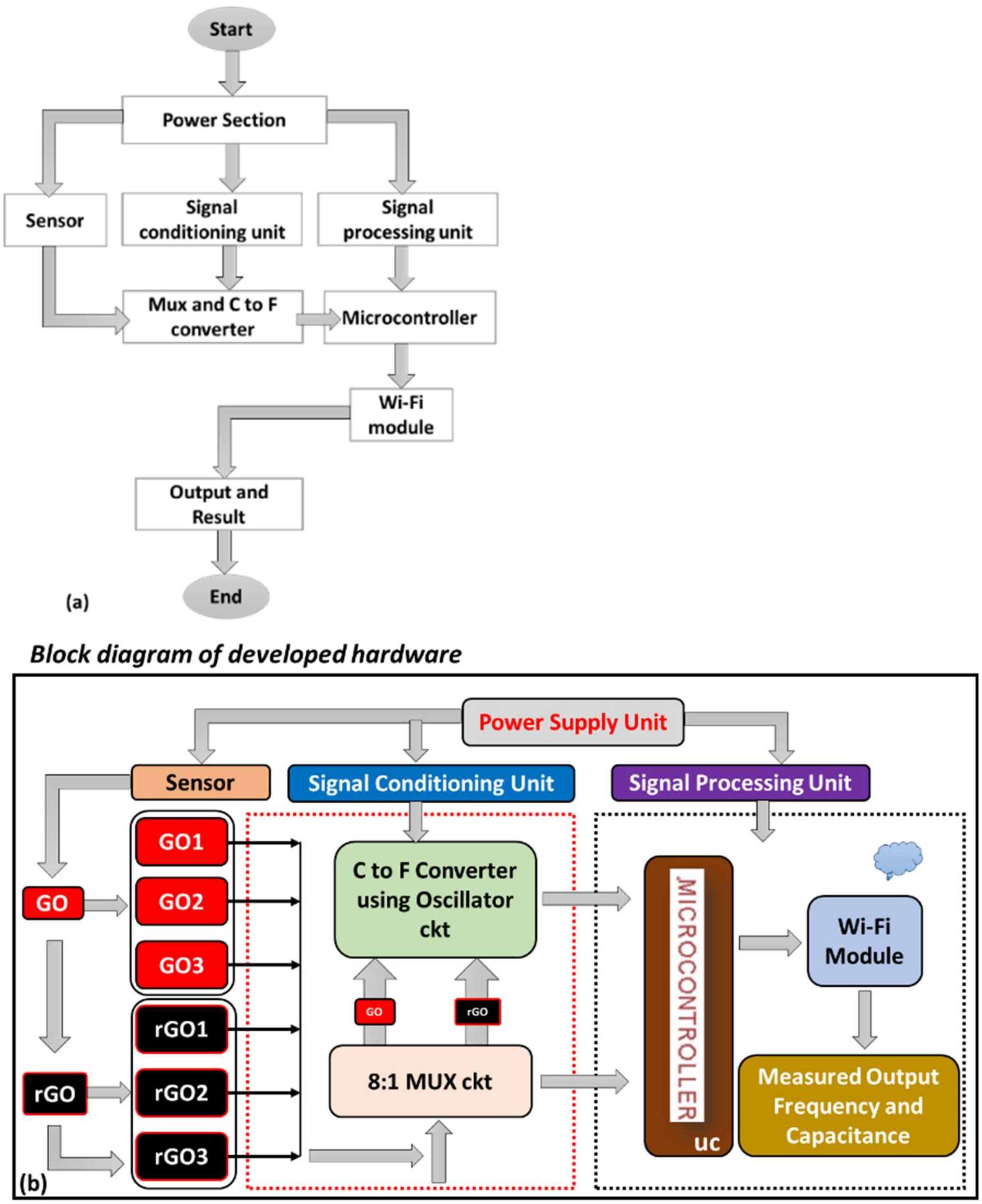


Fig 2: (a) Flow chart for testing of the developed hardware, (b) block diagram for the proposed hardware

The schematic circuit, created using EAGLE software, is illustrated in Fig. 3(a). It comprises four main sections: (i) the main power section, which provides the supply voltage for the entire system; (ii) the 8:1 Mux and C to F converter; (iii) the ESP8266 Wi-Fi module, which transmits data to the server; and (iv) the microcontroller, which oversees the system's operation and manages the sensor output data. Additionally, Fig. 3(b) presents the layout design of the circuit, detailing the routing of the schematic.

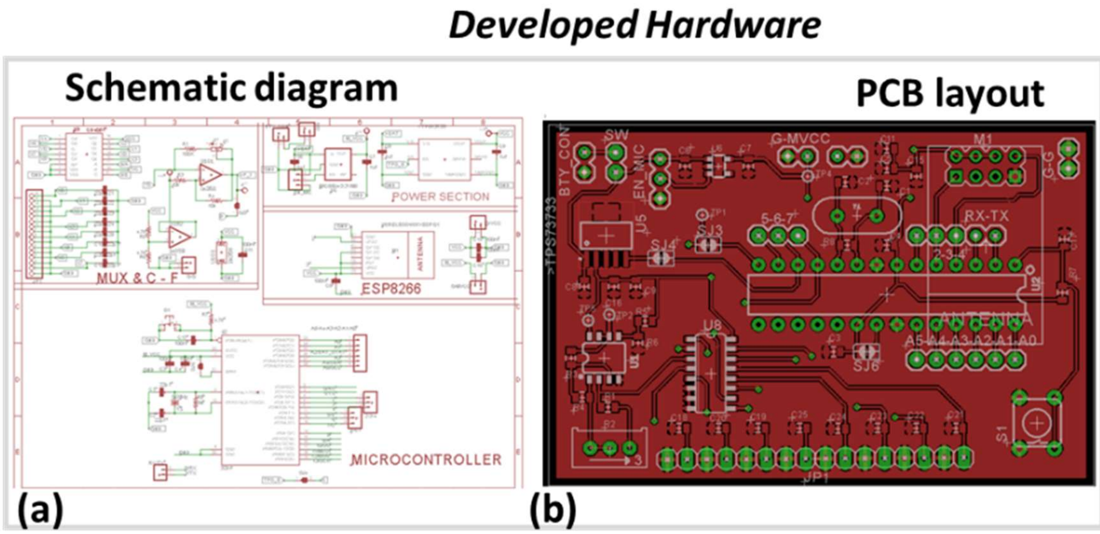


Fig. 3 (a) Proposed schematic circuit and (b) PCB layout design with Eagle software.

Further From Fig. 4 depicted capacitance measurement using LCR meter, GO and rGO sensors connected to an LCR meter, covering the entire area with and without soil samples while measuring capacitance values as shown in Fig. 4 (a), Fig. 4 (b) respectively. similarly, same procedure followed by different derivatives of GO1, GO2, GO3, and rGO1, rGO2, rGO3 respectively.

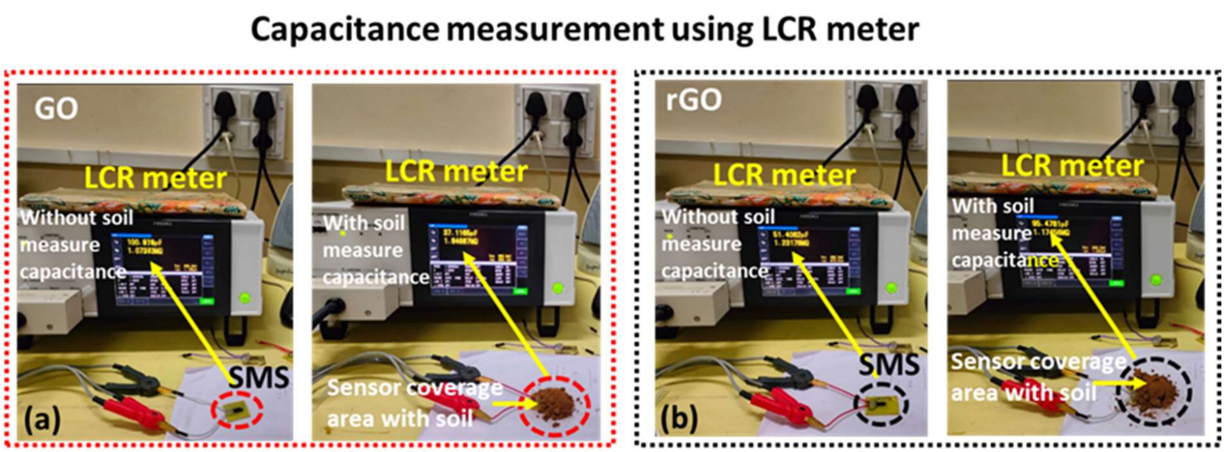


Fig. 4 (a) fabricated GO sensor connected with LCR meter with and without soil (b) fabricated rGO sensor connected with LCR meter with and without soil

3. Results and discussion

- **3.1 Simulation**
  After designing the developed hardware using signal conditioning circuit, the design is checked in Tina

Ti software and each component is tested separately by being soldered onto a PCB board. Testing has been carried out on Tina-TI for the software simulation of the proposed hardware circuit. The Signal conditioning unit, in this software was tested. The relaxation oscillator, which is a C to F converter, received testing first.

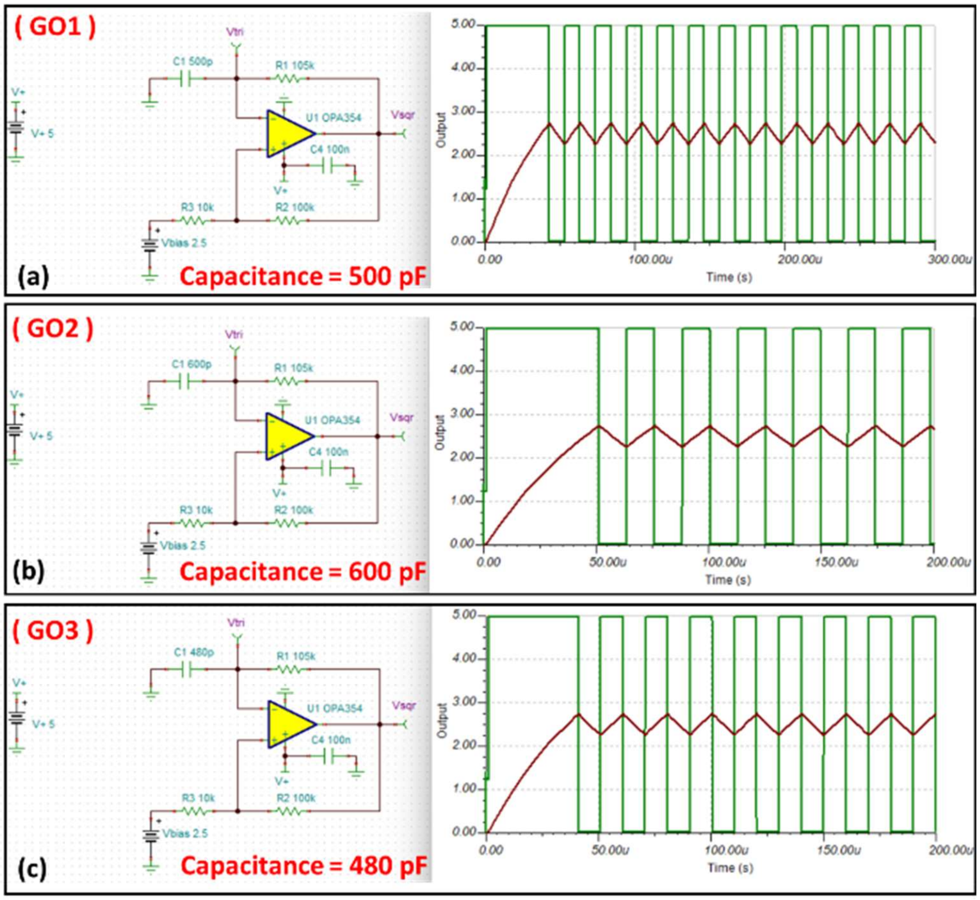


Fig. 5 Simulation result for the oscillator circuit using TINA TI software (a) GO1 with capacitance value 500 pF (b) GO2 with capacitance value 600 pF (c) GO3 with capacitance value 480 pF

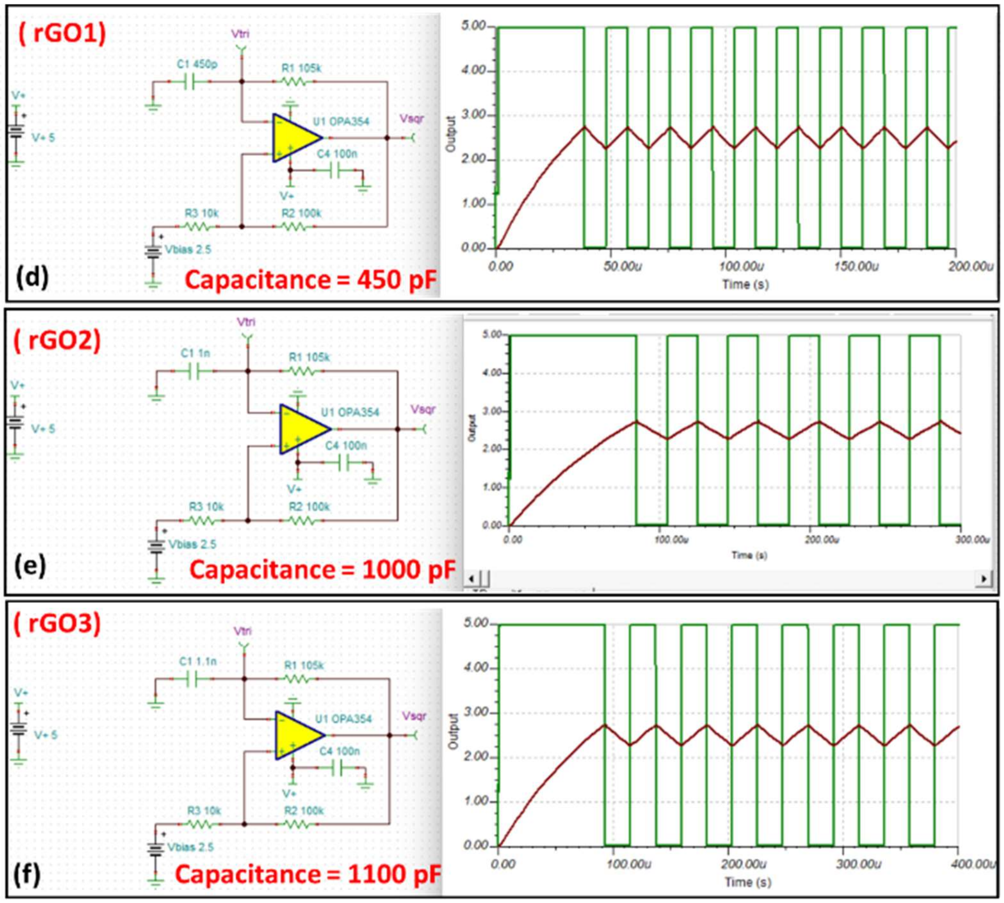
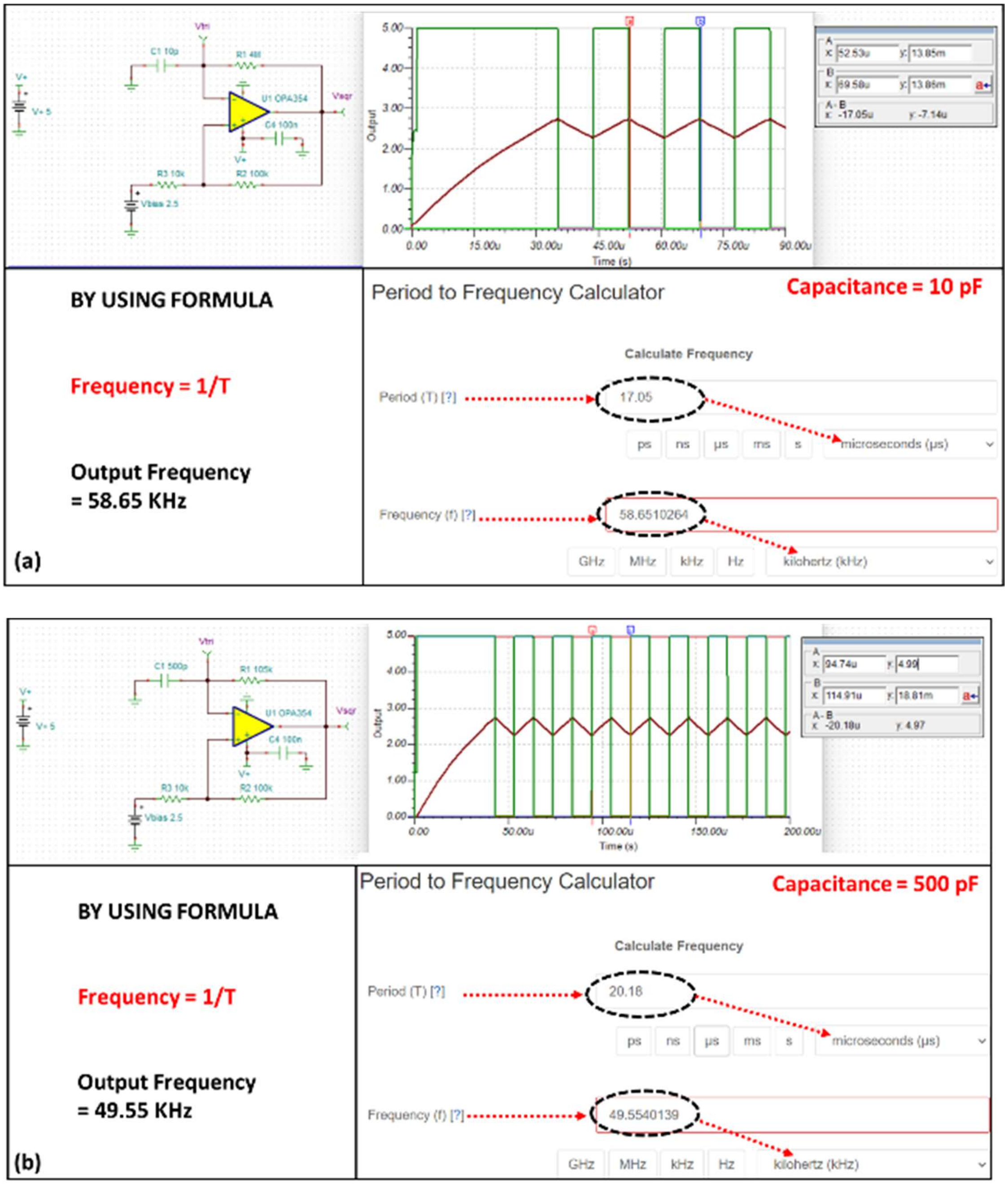


Fig. 5 Simulation result for the oscillator circuit using TINA TI software (d) rGO1 with capacitance value 450 pF (e) rGO2 with capacitance value 1000 pF (f) rGO3 with capacitance value 1100 pF

Figure 5 displays the concentration of the different GO and rGO derivatives (GO1, GO2, GO3, and rGO1, rGO2, rGO3) that were tested. The result of the GO1 sensor simulation for a minimum capacitor of 10 pF is displayed in Fig. 5(a), followed by GO2's capacitance value of 600 pF and GO3's capacitance value of 480 pF in Figs. 5(b) and 5(c), respectively.

The output of the rGO1 sensor simulation is displayed in Fig. 5(d) with a capacitance value of 450 pF, followed by the rGO2 sensor output with a capacitance value of 1000 pF, and finally the rGO3 sensor output with a maximum capacitance value of 1100 pF as illustrated in Fig. 5(e) and Fig. 5(f), respectively.

Further From Fig. 6 The formula f = 1/T is used to further translate these capacitance values into frequency (detail explained under (3.1) in Section 3). Using a period to frequency converter, we converted the values of the hear minimum, maximum, and between ranges capacitance into frequencies, as shown in Fig. 6. After carrying out this evaluation the output frequency is 58.65 KHz when the minimum capacitance value is 10 pF, as shown in Fig. 6 (a). similarly, When the minimum capacitance value is 500 pF, as shown in Fig. 6 (b), the output frequency is 49.55 KHz. Following the completion of this measurement the output frequency is 22.68 KHz when the maximum capacitance value is 1100 pF, as shown in Fig. 6 (c).


BY USING FORMULA
Frequency = 1/T
Output Frequency
= 58.65 KHz
(a)
Period to Frequency Calculator
Capacitance = 10 pF
Calculate Frequency
Period (T) [?]
17.05
microseconds (µs)
Frequency (f) [?]
58.6510264
kilohertz (kHz)
BY USING FORMULA
Frequency = 1/T
Output Frequency
= 49.55 KHz
(b)
Period to Frequency Calculator
Capacitance = 500 pF
Calculate Frequency
Period (T) [?]
20.18
microseconds (µs)
Frequency (f) [?]
49.5540139
kilohertz (kHz)

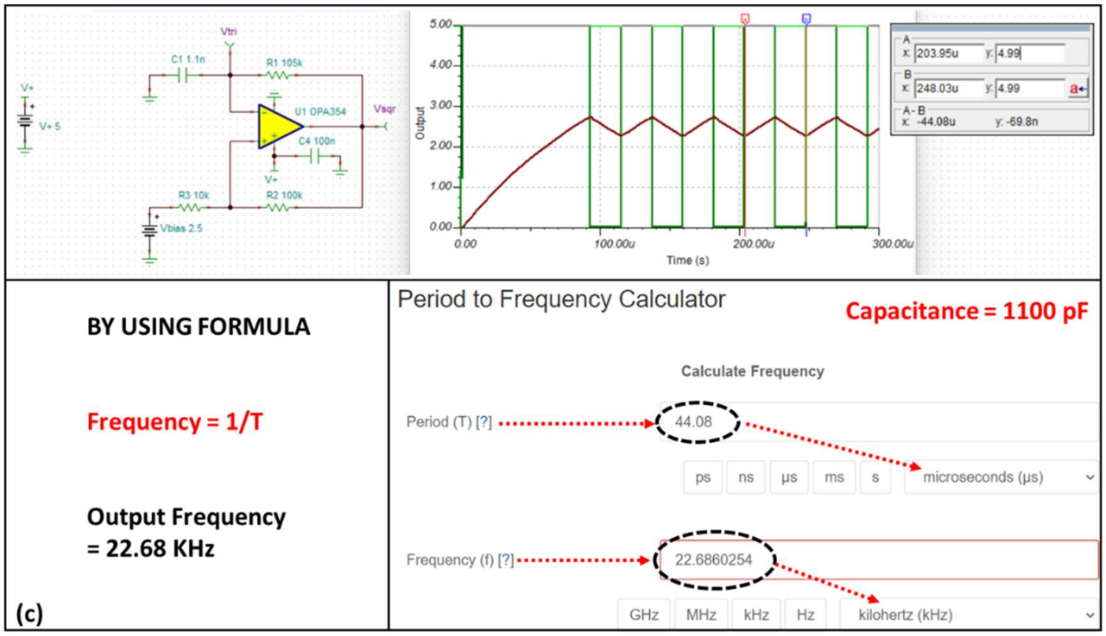
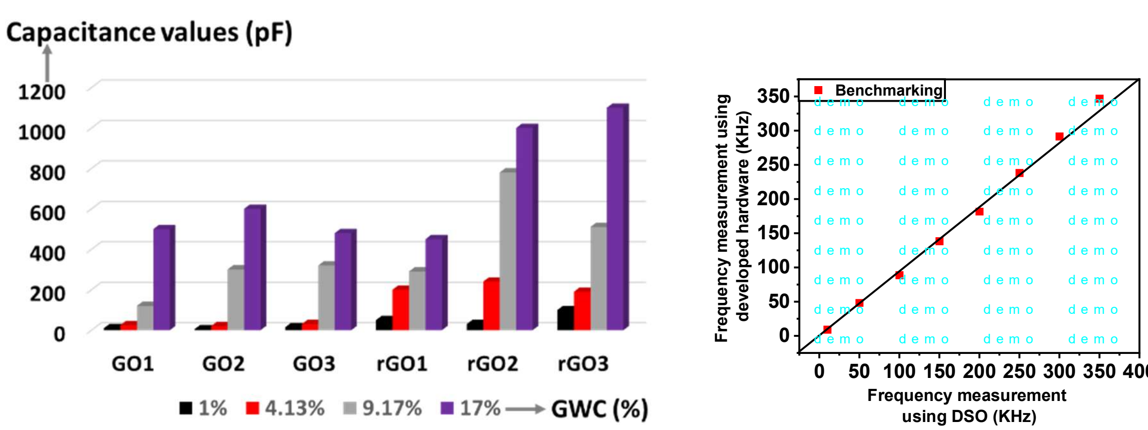


Fig.6 Simulation result for the oscillator circuit using TINA TI software with using period to Frequency Calculator (a) Minimum capacitance value 10 pF (b) In between capacitance value 500 pF (c) Maximum capacitance value 1110 pF

- ***3.2 Lab testing***

Furthermore, accuracy in measuring capacitance using the developed hardware is vital to avoiding measurement system errors. According to a fabricated sensor (GO1, GO2, GO3, rGO1, rGO2, rGO3) with varying soil moisture water content, Fig. 7(a) shows a bar graph of various capacitance values. likewise, the measured frequency utilising the developed hardware must be exact in order to avoid inaccuracy in the measuring systems. Fig. 7 (b) depicts the measured frequency value utilising DSO with developed hardware, demonstrating high linearity between both methods used for frequency measurements. Fig. 7 (c) We presented lab results with some output frequencies that were generated using developed hardware for fabricated sensors. From Fig. 7(c), the output GO frequencies are (a) 69.80 KHz, (b) 91.14 KHz, (c) 53 KHz, and (d) 116.0 KHz, (e) 66.54 KHz, (f) 68.1 KHz for the rGO output frequencies respectively.



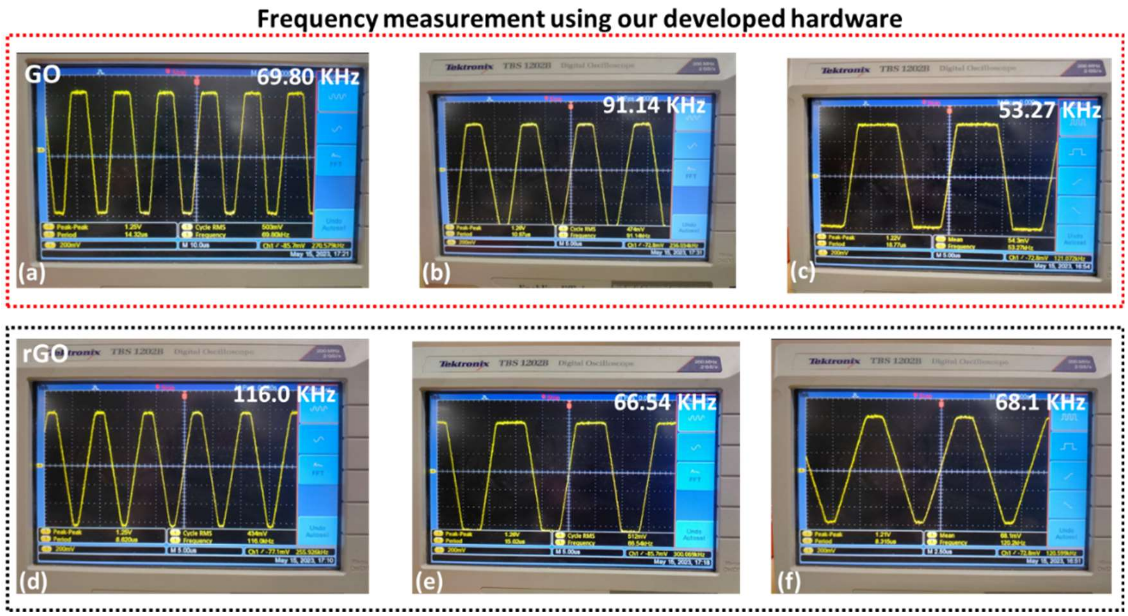


Fig 7: (a) The measured capacitance using proposed hardware with different GWC (%), (b) benchmarking of the measured frequency using DSO and developed hardware, (c) output frequency using developed hardware for fabricated sensor GO and rGO (a, b, c, d, e, f)

3.3 IOT Data transmission to MATLAB

The proposed analog circuit described above converts changes in capacitance to frequency, which is measured using a microcontroller known as data acquisition. As depicted in Fig. 3.a, the ESP8266 (a Wi-Fi module) is connected to the microcontroller via a UART interface, functioning as the transmitting module. The Wi-Fi module sends the data to a server, making it accessible from anywhere, and it also transmits all collected data to MATLAB's ThingSpeak. MATLAB's ThingSpeak API processes the real-time data. The data sent by the Wi-Fi module is received by MATLAB's ThingSpeak and used for data visualization and to publish the transmitter module's data to the Internet of Things.

Conclusion

This paper presents the development of an affordable, portable, and cost-effective IoT-enabled soil moisture measurement system. The system features capacitive sensors based on graphene oxide (GO) and reduced graphene oxide (rGO) as key components to measure gravimetric moisture content by detecting changes in capacitance. The pro-posed analog front-end circuit, simulated in Tina-TI, measures these changes and has been benchmarked against a commercial DSO meter to evaluate measurement error. The designed analog circuit converts capacitance changes into frequency variations, which are then measured by a microcontroller. The microcontroller detects these fre-quency changes via GPIO and transfers the data to a server. The data on the server is accessed by MATLAB's ThingSpeak for further analysis.

Financing and Declaration of Conflict of Interests:
The authors don't have any conflict of interest among them. The authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest or non-financial interest (such as personal or professional relationships, affiliations, knowledge, or beliefs) in the subject matter or materials discussed in this manuscript.

Ethical Approval: This article does not contain any studies with human participants or animals performed by any of the authors.

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