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Laboratory Evaluation of Soil Moisture Sensors for Precision Irrigation in Agriculture

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Authors' contributions

This work was carried out in collaboration among all authors. Authors AAR and HN prepared the research work and drafted the manuscript. Authors CKK and SM prepared the report. Author MKG provided guidance. All authors read and approved the final manuscript.

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ABSTRACT

Water is essential for agricultural production and food security, making efficient water use critical. Accurate measurement of soil moisture is vital for scheduling irrigation, ensuring that crops receive the right amount of water at the right time. This prevents both under- and over-irrigation, conserving water and maximizing crop production. Currently, digital soil moisture sensors are used for their accuracy and instant measurement capabilities. The soil moisture sensor's functionality was evaluated through observations of four Capacitive soil moisture sensors 1.2 (SMS A, B, C, D) at various moisture levels, with gravimetric method verification. The calibrated linear equations demonstrated a strong linear relationship for each sensor. The coefficient of determination (R^2) were also found to be 0.92, 0.93, 0.91 and 0.93 respectively. These R^2 values indicate a strong linear relationship for each sensor. An automated drip irrigation module was developed by integrating these soil moisture sensors with the Arduino platform. The system activates the

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irrigation motor when soil moisture content falls below the field capacity or a desired set value, and turns it off once the required moisture level is reached. This sensor-based automated drip irrigation module enables farmers to irrigate their fields precisely and efficiently, delivering the right quantity of water at the right time. The system is also suitable for deficit irrigation practices, improving crop yield and water use efficiency.

Keywords: Soil moisture; field capacity; sensor; arduino; automatic irrigation; water use efficiency.

1. INTRODUCTION

Water is essential for agriculture production and food security, making efficient water use critical. Water is a vital natural resource that is essential to all life on Earth and is also a fundamental component of sustainable development. Worldwide water supplies are under more stress due to a geometric increase in population and the fast urbanization, industrialization, and agricultural expansion that is occurring. Approximately 2 billion people need access to safe drinking water, and 3.6 billion need access to properly managed water and sanitation, according to the UN World Water Development Report 2024 [1-4]. It is estimated that by 2050, the world's water demand will rise by 20–25% (United Nations World Water Development Report 2018). Particularly in Sub-Saharan Africa, population growth and growing irrigation requirements would result in a 163% increase in water demand (African Development Bank Report on Water Security in Sub-Saharan Africa) [5-9]. Approximately 80% of the freshwater resources in our nation are used by the agriculture sector in India. However, because of rising demand from other industries brought on by the country's constantly expanding population, its proportion is predicted to drop to 69% by 2025 in India (Government of India, Ministry of Water Resources, Central Water Commission Report 2020). It is projected that by 2050, around 22% of India's land area will experience complete water scarcity, and by 2025, 1800 million people will reside in such nations [10].

Innovations in science and technology are possible in an environment of Information Technology (IT) development and the rise of free and open-source solutions [11,12-15]. Effective water monitoring is one of the essential measures to accomplish sustainable water resource management in relation to the scientific and technological strategies to reduce water scarcity. Apart from reducing water scarcity, water monitoring specifically, soil moisture content monitoring helps guarantee that crops can develop in an useful way [16-18].

The soil moisture sensor-based scheduling system is severely limited by the spatial variability of soil moisture, problems with sensor installation, challenges in accurately reflecting the whole root zone, sensor calibration, and measurement errors when there is gravel present. The most accurate method used for soil moisture content is the gravimetric method [19,20-24]. However, the gravimetric method is destructive, laborious, and does not 3 allow for real-time measurement of soil moisture content. Conversely, ET-based irrigation methods mostly depend on evaluating local climatic data. Crop coefficients used in ET-based irrigation strategies are specific to each area and may not be accurate [25-31]. Because cumulative errors can occur with computed ET-based scheduling systems, field-based measurements are usually necessary to adjust or recalibrate ET-based irrigation recommendations [19,32-38].

2. MATERIALS AND METHODS

2.1 Experimental Location

The proposed research on the development and evaluation of a sensor-based drip irrigation system was conducted at the Department of Soil and Water Conservation Engineering, College of Agricultural Engineering, Kandi, Sangareddy, PJTSAU Rajendranagar, Hyderabad. This location is situated at a latitude of 17° 9' 36" N and longitude of 78° 16' 48" E, with an elevation of 535 meters above mean sea level.

2.2 Components of Sensor Based Drip Irrigation

A soil moisture sensor was created and calibrated using the standard gravimetric method of measuring soil moisture, and tested in various soil moisture sensors types to assess its performance. The physical parameters of the soil were determined, and the data, along with the sensor that was developed, was programmed in C++ and incorporated onto the Arduino platform to enable the irrigation module to be automated. The system that created an automatic drip irrigation module completed operational testing and performance evaluation.

Fig. 1. Experiment location in College of agriculture Enginnering, Sangareddy

A sensor setup installed, based on the specifications of the field [19]. A capacitive soil moisture sensor (v2.0), a temperature and relative humidity sensor (DHT11), form an individual model field data collection devices. The Arduino is programmed to gather data from many sensors, including temperature, relative humidity, and soil moisture, and to plot that data as a separate field graph using the C++ programming languages. A capacitive soil moisture sensor (v2.0) is used to measure soil moisture at a depth of 15 cm, while a DHT11 sensor gathers temperature and humidity. According to its ultimate installation at the start of the winter season, the system required roughly two months being developed and tested at the research site.

STEPS:

1. Using jumper wires, attach the soil moisture sensors and DHT11 to the Arduino board.
2. Using jumper wires, attach the relay module to the Arduino board.
3. Using jumper wires, connect the water pump to the relay module.
4. Using jumper wires, connect the liquid crystal display to the Arduino board.
5. Install the Arduino board driver and the Arduino IDE on the PC.
6. Download the Arduino IDE, then start a fresh project.
7. Select Sketch -> Include Library -> Manage Libraries in the Arduino IDE.
8. Install the Arduino library by searching for it.
9. Upload the code to the Arduino board

2.2 Virtual Development and Simulation of Soil Moisture Sensors using Tinker Cad

Tinker Cad was an online tool that allowed users to create and simulate 3D models, catering to both novices and experts alike. In the field of electronics and engineering, Arduino was recognized as a powerful tool, serving as an open-source electronics platform. It featured a programmable microcontroller capable of controlling LEDs, motors, sensors, and other electronic components. Programming for Arduino boards was typically done in languages like C and C++, with boards available in various sizes and designs. The Arduino board collected data from soil moisture sensors, determining the optimal watering schedule for plants based on the gathered data. A relay module was used to manage the water pump, activating it when soil moisture levels dropped below a set threshold, thereby ensuring plants received water as needed.

2.3 Calibration of the Developed Soil Moisture Sensor

The calibration of the developed soil moisture sensor was done taking soil in the laboratory. The standard gravimetric method [19] was used to determine the moisture content of the soil based on volume. A sample of wet soil was weighed and dried for 24 hours at 105ºC in the oven. The device used to measure the weight was a digital weighing balance.

2.4 Validation and Performance Evaluation of the Soil Moisture Sensor

The measurements from the soil moisture sensor were obtained at different moisture levels using four separate sensors (SMS A, SMS B, SMS C, and SMS D). In order to validate the current moisture content data, ten soil samples were employed (Plate 3). Samples of soil with various moisture contents were gathered from various locations. Simultaneous recordings of analogue readings were made from the soil moisture sensors. To determine the real moisture content of the soil samples that were collected, the gravimetric method was applied in the laboratory. To compare the soil moisture content measured by the gravimetric approach with the analogue values from the soil moisture sensor, a linear graph was created.

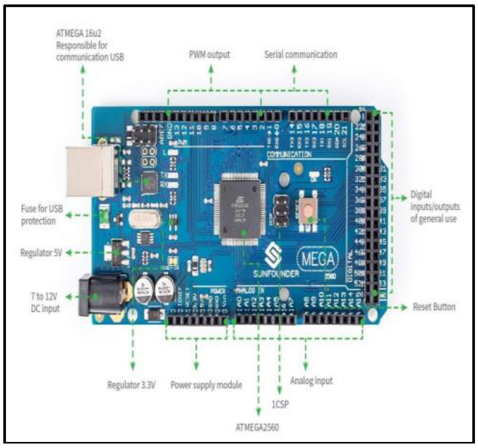

Plate 1. Arduino board

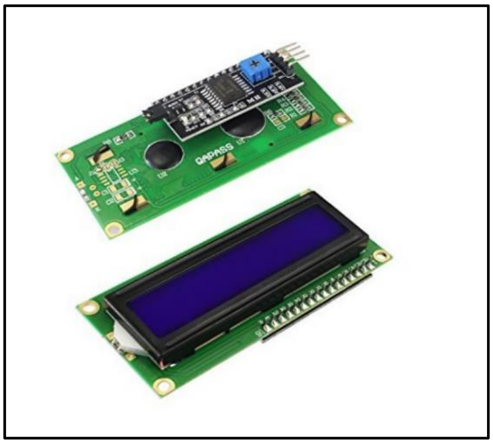

Plate 2. Liquid crystal display

Plate 3. Capacitive soil moisture sensor v1.2

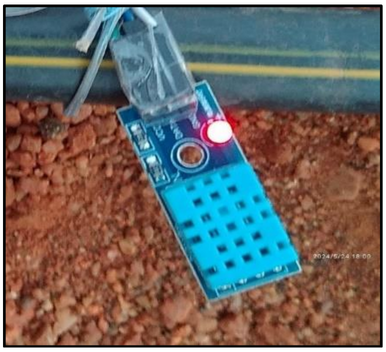

Plate 4. Temperature & Humidity sensor

Plate 5. Electrical motors (0.5 hp)

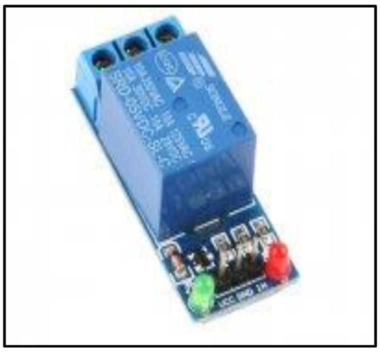

Plate 6. Relay module

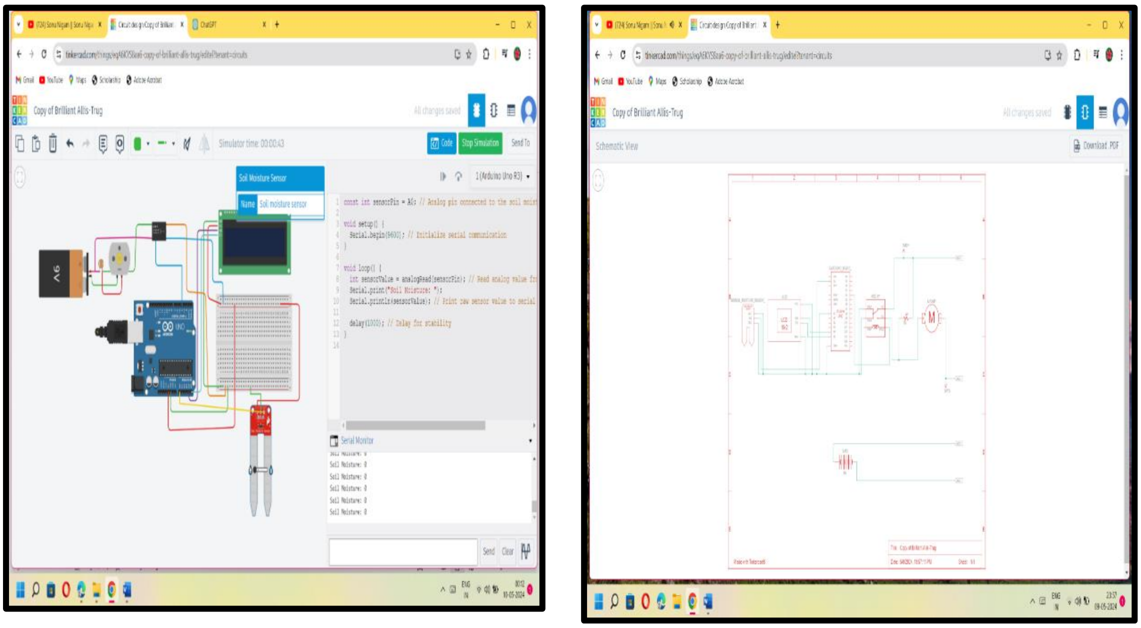

Fig. 2. Virtual Experimentation of Sensor Systems in Tinker Cad

Plate 7. Calibration of sensor in lab

Plate 8. Sample in oven dry

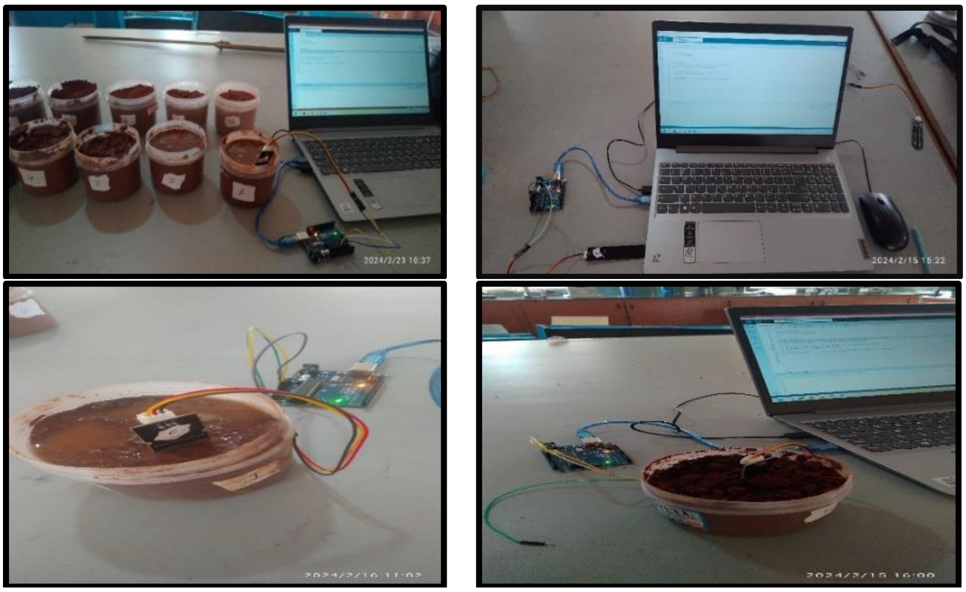

Plate 9. Measurement of soil moisture by the developed sensor (SMS A, SMS B, SMS C, SMS D)

Plate 10. Development of the soil moisture sensor

3. RESULTS AND DISCUSSION

3.1 Development of the Soil Moisture Sensor

The soil moisture was developed following the procedure as mentioned in the materials and methods. Each of these parts was linked in accordance with designated pins in order to be assembled in plate 1 using an Arduino. The Arduino was configured with the soil moisture sensor's VCC pin linked to 5V, GND pin connected to ground, and OUT or SIG pin connected to an analogue input pin (such as A0) for measuring moisture levels. In order to control equipment like water pumps, the relay module needed connections where the IN1 pin was connected to a digital output pin (such pin 7), GND to ground, and VCC or JD-VCC to 5V. The VCC and GND pins of the LCD display were linked to the Arduino's 5V and ground, respectively. Its SDA and SCL pins were linked to the Arduino's corresponding SDA (A4) and SCL (A5) pins in order to enable I2C protocol communication. This configuration made it possible for the Arduino to communicate with and manage these parts, making it easier to do things like track soil moisture, turn on irrigation systems, and synchronise the information displayed on the LCD panel.

3.2 Soil Physical Properties

Bulk density is the mass of soil per unit volume, including the air space. A bulk density of 1.3 g/cm^3 indicates a moderately dense soil structure, which affects root penetration, water movement, and soil aeration. The quantity of water content or soil moisture that remains in the soil after surplus water has drained away and the rate of downward movement has slowed down is known as field capacity. The soil can hold 22.15% of its volume in water when it has a field capacity of 22.15%. The permanent wilting point of 9.2% indicates the soil moisture level at which plants begin to experience irreversible wilting due to insufficient water.

3.3 Calibration of the Moisture Sensor

The observations on volumetric soil moisture content and analogue values by the sensor for calibration have been presented in Table 1. After developing the calibrated equation, it was discovered to be linear in nature; this is shown in Fig. 3. This is the developed equation.

$$Y = -0.1271x + 54.053 \quad (R^2 = 0.931) \quad (3.1)$$

Where,

R = Correlation value between the developed soil moisture sensor and the standard moisture determination method

y = Moisture value of the developed sensor

x = Moisture value by standard method

3.4 Validation and Performance Evaluation of the Developed Soil Moisture Sensor

The developed soil moisture sensor was verified and its functionality evaluated by making observations in four different soil moisture sensors namely SMS A (Capacitive soil moisture sensor1.2), SMS B (Capacitive soil moisture sensor1.2), SMS C (Capacitive soil moisture sensor1.2), and SMS D (Capacitive soil moisture sensor 2.0) at various moisture levels, with the associated soil moisture values detected by the use of the gravimetric method. The observations used to validate the designed soil moisture sensor for various soil types are shown in Table 2. The developed sensor's regression relationships with the gravimetric method's moisture content for various soils are shown in Fig. 4. The calibrated linear equations demonstrated a strong linear relationship for each sensor. For SMS A, the equation is $y = -0.1303x + 58.084$, with an R^2 value of 0.9229. For SMS B, the equation is $y = -0.1271x + 54.053$, with an R^2 value of 0.931. For SMS C, the equation is $y = -0.0957x + 42.631$, with an R^2 value of 0.9109. For SMS D, the equation is $y = -0.1238x + 59.762$, with an R^2 value of 0.9314. These R^2 values indicate a strong linear relationship for each sensor.

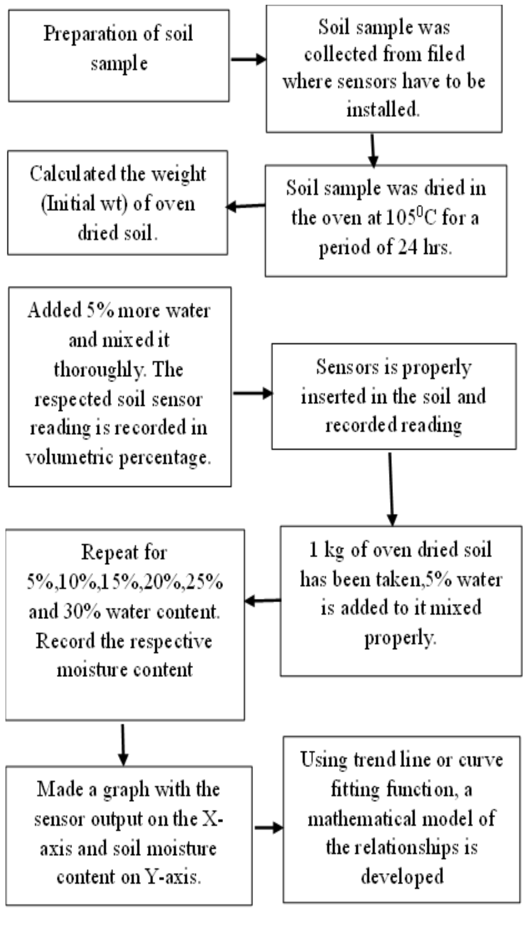

Fig. 3. Flowchart of the Calibration

Table 1. Specifications, description and function of the hardware placed inside the data acquisition system

1.Capacitive Soil Moisture Sensor V2.0: • **Specifications**: Operating Voltage: 3.3 to 5.5 VDC, Operating Current: 5mA, Output Voltage: 0 to 3 VDC, Accuracy: ±2% • **Function**: Detects soil moisture levels.	**4.Relay**: • **Specifications**: Operating Voltage: 220 VAC, Size: 3/4", Pressure: 1 to 10 Kgf/cm, Coil Protection: 24VDC. • **Function**: Actuates the relay module and pump for automatic irrigation.
2.DHT11: • **Specifications**: Operating Voltage: 3.5 to 5.5V, Operating Current: 0.3mA, Temperature Range: 0°C to 50°C, Humidity Range: 20% to 90%, Resolution: 16-bit for both temperature and humidity. • **Function**: Measures ambient temperature and relative humidity.	**5.Pump**: • **Specifications**: Power: 0.75 kW / 1.02 HP, Head: 23.5m, Discharge: 1.4 lps, Voltage: 210V. • **Function**: Drives motor gears for water pumping.
3.Microcontroller (Arduino): • **Specifications**: Operating Voltage: 3.5 to 5.5V, DC Current per I/O Pin: 20mA, DC Current for 3.3V Pin: 50mA. • **Function**: Processes algorithms for system control.	**6.Display (LCD)**: • **Specifications**: Display Type: Monochrome LCD, Resolution: 16x2 characters, Screen Size: 2.5", Operating Voltage: 5V. • **Function**: Displays

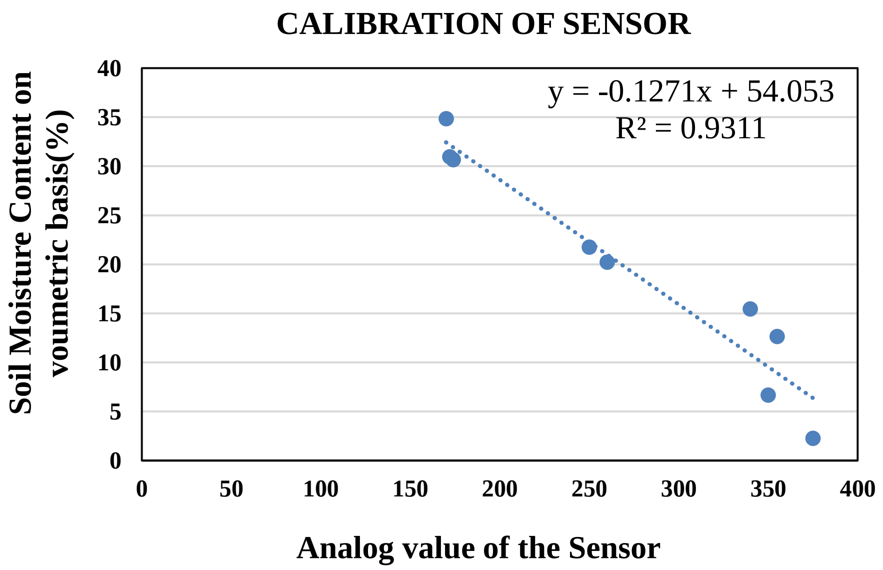

Fig. 4. Calibration equation for the developed soil moisture sensor

Table 2. Calibration of the moisture sensor

Sl. No.	Volumetric soil moisture content by gravimetric method (%)	Analog value of the developed sensor
1.	34.84	170
2.	30.96	172
3.	30.66	174
4.	21.76	250
5.	20.23	260
6.	15.47	340

Sl. No.	Volumetric soil moisture content by gravimetric method (%)	Analog value of the developed sensor
7.	12.65	355
8.	6.66	350
9.	2.28	375
10.	0	450

Table 3. Observation for validation of the soil moisture sensor A, B, C, D

Sample	Water (ml)	SMS A	SMS B	SMS C	SMS D	VMC(%)
1	180	210	170	120	230	34.84
2	160	220	172	130	240	30.96
3	140	230	174	170	260	30.66
4	120	240	250	190	280	21.76
5	100	270	260	210	290	20.23
6	80	340	340	270	360	15.47
7	60	350	355	310	390	12.65
8	40	370	350	340	410	6.66
9	20	400	375	370	430	2.28
10	0	480	450	510	520	0

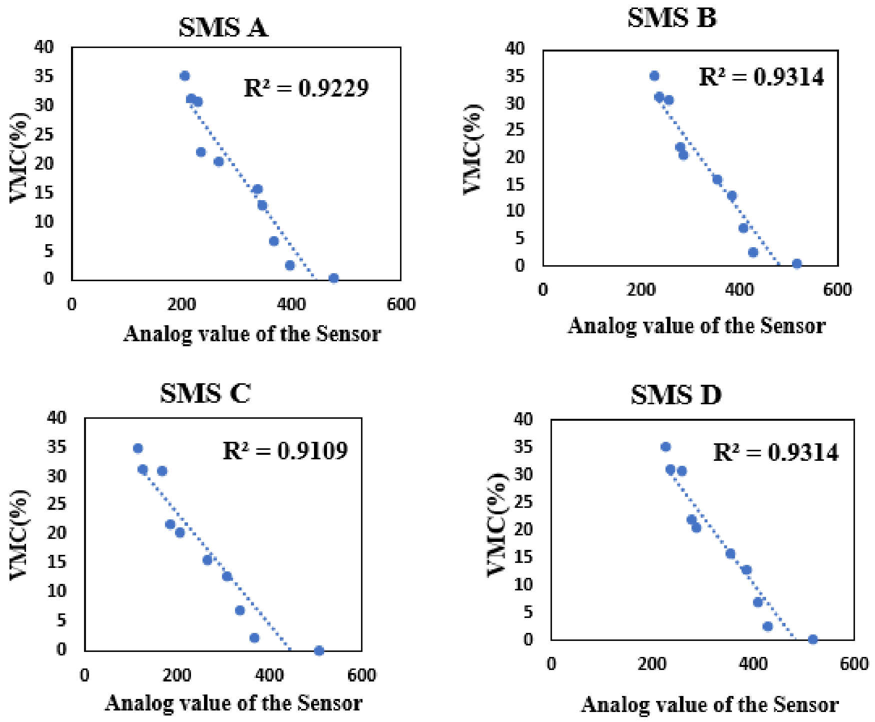

Fig. 5. Relationship between analogue value by sensor and gravimetric method in SMS A,B,C,D

4.SUMMARY AND CONCLUSION

Water and soil are two vital natural resources that are important to agriculture. Due the scarcity and high cost of irrigation water, effective irrigation management is necessary since agriculture uses a significant amount of water. A well-planned irrigation schedule can greatly increase crop yield and growth. Accurate soil moisture measurement is necessary for achieving this. Digital soil moisture sensors are frequently used in modern agriculture to track soil moisture levels in real time. There are multiple types of soil moisture sensors on the market. A new sensor-based automated drip irrigation module was created in order to overcome these limitations.

The moisture sensor was calibrated with standard gravimetric method and the calibration equation was found to be linear in nature, Y= -0.1271x + 54. An sensor based irrigation module was integrated through programming on the Arduino platform, incorporating the developed soil moisture sensor. The system was then tested with four different soil moisture sensors to ensure its versatility and reliability across various conditions. In this trial, sensor-based irrigation seems to be the more successful treatment.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc have been used during writing or editing of mauscripts. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology

Details of the AI usage are given below:

1. CHAT GPT
2.Quillbot

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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