Journal of Scientific Research and Reports

Volume 30, Issue 5, Page 547-555, 2024; Article no.JSRR.115020
ISSN: 2320-0227

Innovative Module Design for Advanced Automated Irrigation Systems

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Authors' contributions

This work was carried out in collaboration among all authors. Authors RY designed the study. Authors RY, JS, HG involved in data curation. Authors RY, AK, Sangeeta wrote the first draft of the manuscript. Authors RY, AK, and IS managed the analyses of the study. Authors JS, Sangeeta and HG a helped in literature searches. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/JSRR/2024/v30i51970

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/115020

Received: 20/01/2024
Accepted: 26/03/2024
Published: 29/03/2024

Original Research Article

ABSTRACT

Aim: The paper aims to develop a soil moisture sensor utilizing copper material to enhance irrigation efficiency in regions like India. Calibration using the gravimetric method showcased the sensor's superior performance across various soil types. Integrated with an Arduino platform, an

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automated irrigation module was successfully tested. The developed system offers a practical solution for automated irrigation, even in water-scarce environments.

Methodology: The study conducted in the Soil and Water Conservation Engineering Laboratory involved fabricating a soil moisture sensor with copper material. The experimental setup comprised four units: power supply, sensing, controller, and display. Calibration involved the standard gravimetric method to establish a linear equation correlating moisture sensor readings with soil moisture content.

Results: Calibration revealed a linear relationship between the developed sensor's analog values and soil moisture content. Validation against the gravimetric method demonstrated high accuracy across the tested soil types and depths. Statistical analysis yielded low RMSE values (1.02, 1.013, and 1.022), high R^2 values, and a satisfactory NSE (0.90, 0.90, 0.89), confirming the sensor's reliability and precision.

Conclusion: The developed soil moisture sensor, validated through rigorous testing, demonstrates superior performance across tested soil types. Integrated into an automated irrigation module, it offers an efficient solution for irrigation automation, contributing to water conservation and improved crop productivity.

Keywords: Soil moisture; sensor; arduino platform; calibration; gravimetric method.

1. INTRODUCTION

Effective use of existing water resources is a critical issue for countries like India, which has a large population share of 17% and only 2.4% of the world's landmass and 4% of its water resources [1]. It is estimated that the nation has a total irrigation potential of 139.5 million hectares (Mha), of which only 60.8% are currently being used [2]. The accurate soil moisture evaluation becomes imperative to enable the accurate scheduling of irrigation, which is necessary for crop production [3]. This project is essential to reducing the effects of both over- and under-irrigation, which promotes water conservation and increases crop productivity. The development of sophisticated methods and techniques for the real-time gathering of accurate soil moisture readings across varied depths is essential to optimizing soil water management [4]. These days, soil moisture sensors are used to determine soil moisture levels more precisely. Effective irrigation scheduling techniques can be put into place to maximize crop cultivation methods in agricultural fields by utilizing such data. The gravimetric method stands out as the most precise technique for determining soil moisture content [5]. However, the destructiveness, labor-intensiveness, and inability of this technology to deliver soil moisture content readings in real time are its main drawbacks. Alternative techniques for non-destructive soil moisture content monitoring have gained popularity in recent decades. These include time domain reflectometry (TDR) [6,7], electrical resistance [8], neutron thermalization [9], and electrical capacitance [10]. Notably, as instruments for improving agricultural water and fertilizer management techniques, dielectric-based single-capacitance soil water monitoring sensors have become more and more popular. Significant progress has been made in soil moisture sensor technology to allow for rapid and automatic in-situ readings of soil moisture based on electromagnetic principles.

Installing automated irrigation systems has the benefit of delivering low-volume, high-frequency water applications, which increases output and decreases labour requirements. A soil moisture sensor, control circuitry, gate valve, auto-pumping unit, timing mechanism, and power supply infrastructure are essential components of these automated irrigation systems. This system controls irrigation operations according to the current soil moisture levels and the scheduled irrigation duration. It continuously analyses soil water stress inside the root zone. Low-cost embedded systems have been increasingly popular for a variety of applications in recent years, as demonstrated by the use of platforms like Arduino [11,12]. These commercially feasible embedded technologies could improve task performance [13] and enable wireless data transmission, which would simplify operating processes [14]. It is essential to create affordable automated irrigation technology in order to improve agricultural productivity and water utilization efficiency. To address the needs of a growing population, it's crucial to adopt inventive agricultural methods that not only increase crop production but also promote environmental conservation. Sustainable agricultural practices are greatly enhanced by automated irrigation systems, which minimize water inputs and reduce human intervention. Modern Indian agriculture emphasizes the need for sophisticated irrigation techniques to maximize water management [15].

For automated irrigation operations, a moisture sensor system's accuracy and sensitivity are critical [16]. Another important factor to examine is whether the sensor system will be affordable for the end users [15–17]. However, the difficulty of constructing sensors that can respond to a variety of ambient and soil conditions, as well as the complexity and expense of the circuits needed for high-frequency capacitance readings, have hampered the development of affordable soil moisture sensors. However, new developments in technology indicate that it may be possible to create more affordable soil moisture monitors without sacrificing accuracy. Therefore, efforts should focus on developing user-friendly instruments that are able to assess soil moisture in situ in real time. This would allow irrigation to be automatically started at the best times and stopped when the required levels are reached.

2. MATERIALS AND METHODS

2.1 Description of the Experimental Setup

The research described herein was conducted within the Soil and Water Conservation Engineering Laboratory of the Department of Soil & Water Conservation Engineering, situated within the College of Agricultural Engineering and Technology, OUAT, Bhubaneswar. The laboratory's geographical coordinates lie between 20° 16' 03" N to 20° 16' 00" N latitude and 85° 47' 48" E to 85° 47' 44" E longitude, with an elevation of 45 meters above mean sea level. The soil composition in the area predominantly comprises sandy loam, red lateritic, and silty loam. The experimental setup comprises four primary units: the power supply unit, sensing unit, controller unit, and displaying unit. The power supply unit furnished a 12V voltage to the system. The sensing unit, constructed primarily of copper brass alloy, served to measure moisture content. The controller unit, fashioned from an Arduino Uno microcontroller, orchestrated the entire system, processing input signals and regulating pump operations. The displaying unit comprised a 16×2 LCD screen, employed for presenting moisture content readings.

2.2 Fabrication of the Soil Moisture Sensor

The electrical sensor made use of a single copper metal cylindrical probe. A standard length of 30 cm was used for the probe. One electrode of the sensor was a hollow copper pipe, and the other electrode was a brass capped end that was placed at the tip of the probe. By using a polymer insulator, insulation between the electrodes was guaranteed. Adhesive clay was used to make the assembling of these metal parts easier (Fig. 1A). To keep the space between the two metal electrodes constant, a pneumatic tube was positioned in between them. To display data, two wires that came from the tip electrode and the outside copper tube electrode, respectively, were connected to the circuit board. Electrochemical resistance changed as a result of variations in soil moisture content. The controller unit, which included an LCD unit and an Arduino UNO platform (Fig. 1B), interfaced with the moisture sensor. The source of power was an AC adaptor. Detailed specifications of the developed sensor are provided in Table 1.

Fig. 1(A). Developed soil moisture sensor (sensing unit) (B) Controller and display units

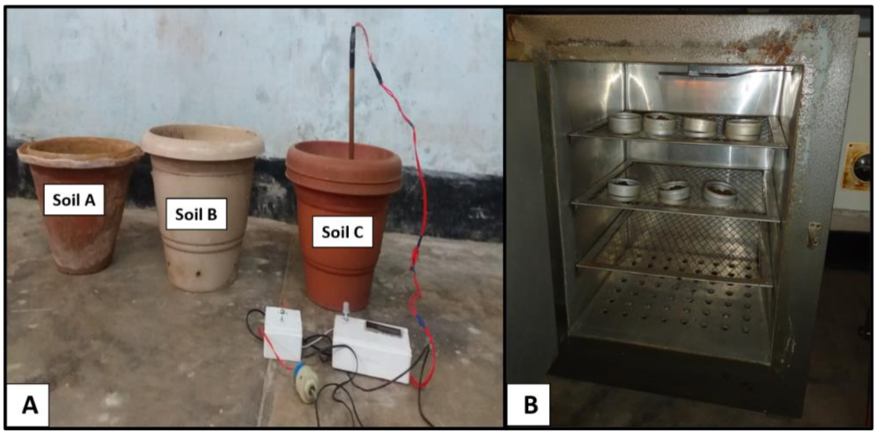

Fig. 2. Soil moisture content measurement (volumetric basis) by (A) the developed soil moisture sensor (B) gravimetric method

Table 1. Specifications of the developed soil moisture sensor

Power source	AC to DC adapter
Voltage rating	12 V
Current	2 A
Measuring characteristics	Electrical resistance
Output type	Analog
Display	16 x 2 LCD (5×7 pixel matrix)
Inner tube	Alloy of copper brass
Inner tube diameter	6.35 mm
Diameter of hollow copper pipe	12.5mm
Length	300mm

2.3 Soil Moisture Sensor Calibration Procedure

The calibration procedure for the developed soil moisture sensor commenced with the collection of soil samples from the central farm, followed by their transfer to the laboratory. These soil samples were then placed within pots and thoroughly saturated with water, allowing them to attain field capacity over a two-day period. Subsequently, the soil moisture sensor was deployed within the pot at a depth of 20 cm, positioned in an open area for continuous monitoring of soil moisture levels. Resistance values recorded by the sensor, along with corresponding soil moisture content values, were recorded daily over a fifteen-day period. Concurrently, soil samples were extracted from the pots at the designated depth each day to ascertain soil moisture content via the standard gravimetric method, thereby facilitating sensor calibration. Upon determining volumetric soil moisture content and corresponding sensor values, a calibration equation was established to correlate the two parameters. This calibration equation was then programmed into the Arduino programme file using the C++ computer language, enabling the sensor to provide moisture content values in percentage.

2.4 Comparison of the Developed Sensor with the Gravimetric Method

A soil moisture sensor was designed, manufactured, and built. It was then calibrated using the standard gravimetric method for measuring soil moisture content. The soil moisture sensor that was constructed was evaluated for effectiveness through validation and performance evaluation in three different soil conditions: soil A (sandy loam), soil B (loamy sand), and soil C (silty loam), at different moisture levels (Fig. 2A). The gravimetric method was used to determine the corresponding soil moisture levels (Fig. 2B). To validate the moisture sensor and determine its accuracy, careful comparison with the gravimetric approach was required. To achieve this, a digital soil moisture meter was used to measure the instantaneous moisture content of each of the three different types of soil. Simultaneously, soil samples were gathered from depths of 0 to 20 cm, corresponding with the sites where the soil moisture meter was produced and moisture measurements were recorded. The moisture content of these soil samples was then ascertained in a laboratory setting using the gravimetric method. Plotting a graph of the soil moisture content obtained by the digital soil moisture sensor and that obtained by the gravimetric approach allowed for a 1:1 comparison to be made to assess accuracy.

2.5 Statistical Analysis

The findings were assessed using three statistical metrics: root mean square error (RMSE), coefficient of determination, and Nash-Sutcliffe Efficiency. The equations (1-3) employed to compute these metrics are outlined below.

i) Root Mean Square Error (RMSE)

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}\left(m_{s,i}-m_{g,i}\right)^2}{N}} \tag{1}$$

The Root Mean Square Error (RMSE) offers the advantage of expressing error in the same units as the variable, providing additional insight into the model's efficiency. A lower RMSE value indicates greater accuracy of the model.

ii) Coefficient of Determination (R^2)

$$R^2 = \frac{\left(\sum_{i=1}^{N}(m_{s,i}-\overline{m_s})(m_{g,i}-\overline{m_g})\right)^2}{\sum_{i=1}^{N}(m_{s,i}-\overline{m_s})^2 \times \sum_{i=1}^{N}(m_{g,i}-\overline{m_g})^2} \tag{2}$$

The coefficient of determination (R^2) quantifies the degree of correlation between observed and predicted values, with values approaching 1.0 signifying strong model performance.

iii) Nash-Sutcliffe Efficiency (NSE)

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{N}(m_{g,i} - m_{s,i})^2}{\sum_{i=1}^{N}(m_{g,i} - \overline{m_g})^2} \tag{3}$$

NSE for an ideal model is 1

Where,

N = Total number of observations
i = Iterations
$m_{s,i}$= Digital moisture sensor values
$\overline{m_s}$= Average of the digital moisture sensor values
$m_{g,i}$ = Gravimetric method values
$\overline{m_g}$ = Average of the gravimetric method values

2.6 Development of an Automated Drip Irrigation Module

The automated drip irrigation module was devised by integrating the developed soil moisture sensor with requisite peripherals. Essential hardware components for the automated irrigation module encompass the interface board (controller unit), DC pump, computer, input and display panel, connectors, adapter, and potentiometer (see Fig. 3A). The Arduino IDE software facilitated the programming of the algorithm. A knob, linked to the potentiometer within the controller unit, enabled the setting of the threshold value for soil moisture content. This predetermined value was visibly displayed on the LCD. Upon detection of soil moisture content dipping below the pre-set threshold, the pump would automatically activate, and conversely, deactivate when surpassing the threshold. Power for the pump was sourced from an AC adapter. The schematic representation of the developed automated irrigation module is depicted in Fig. 3B.

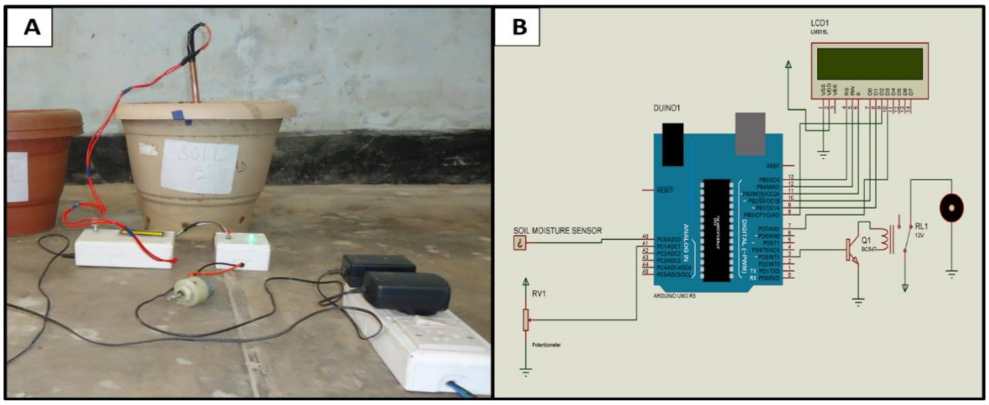

Fig. 3(A). The developed irrigation module (B) schematic diagram of developed module

3. RESULTS AND DISCUSSION

3.1 Moisture Sensor Calibration

The calibrated equation was formulated and observed to exhibit linearity, as illustrated in Fig. 4. The close proximity of the R-squared value to unity signifies a strong linear relationship between the analog value and soil moisture content. Consequently, the sensor demonstrates significant potential for integration into the developed automated irrigation module.

3.2 Validation and Performance of the Developed Soil Moisture Sensor

The regression relationships between moisture content determined by the developed sensor and the gravimetric method for various soil types are depicted in Fig. 5. Across all soil samples, the R-squared values approach unity, indicating high accuracy of the developed soil moisture sensor. Furthermore, Fig. 6 illustrates the comparison of moisture content at different depths measured by both the developed sensor and the gravimetric method. It is evident that, at each depth, the moisture content recorded by the developed sensor closely aligns with that determined by the gravimetric method. No significant disparities are observed between the moisture contents measured by both methods across different depths**.** Statistical indicators were computed based on soil moisture observations obtained from both the sensor and gravimetric method across three distinct soil types, as part of the validation and performance evaluation of the developed soil moisture sensor. The results are summarized in Table 2. It is evident from the table that the Root Mean Square Error (RMSE) values are 1.02, 1.013, and 1.022 for soil A, soil B, and soil C, respectively. Lower RMSE values signify superior performance of the developed soil moisture sensor. The coefficient of determination (R^2) values, ranging from 0.90 to 0.92, indicate a high degree of correlation between volumetric soil moisture detected by the sensor and that determined via the standard gravimetric method. A Nash-Sutcliffe Efficiency (NSE) of 1 (E = 1) signifies a perfect match between the two parameters. NSE values ranging from 0.89 to 0.90 suggest a very good agreement between the sensor readings and those obtained through the gravimetric method. The correctness factor determined for the sensor is ±1.02.

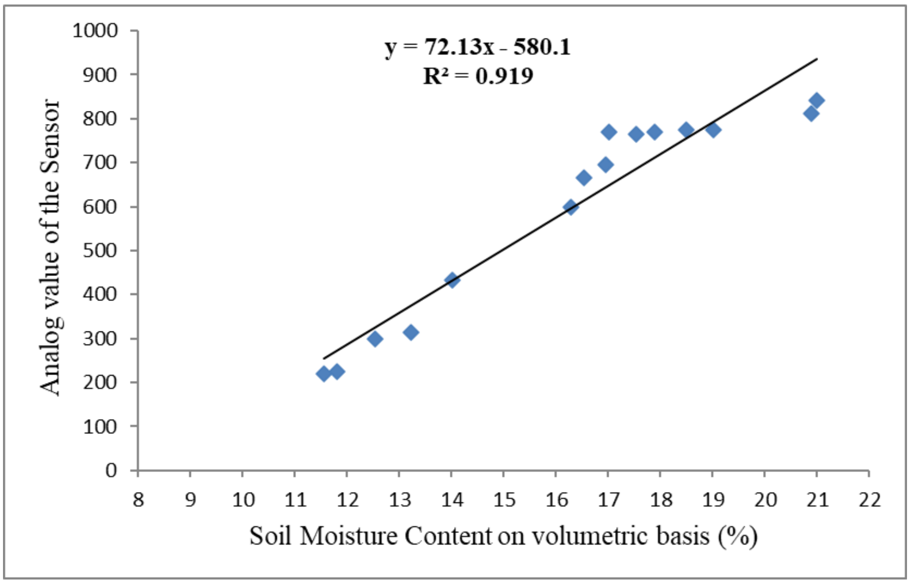

Fig. 4. Calibration of the developed sensor

Table 2. Statistical indicators

Statistical parameters	**Soil type**		
	Soil A	**Soil B**	**Soil C**
Root Mean Square Error (RMSE)	1.02	1.013	1.022
Coefficient of determination (R^2)	0.92	0.91	0.90
Nash-Sutcliffe Efficiency (NSE)	0.90	0.90	0.89
Correctness coefficient	± 1.02		

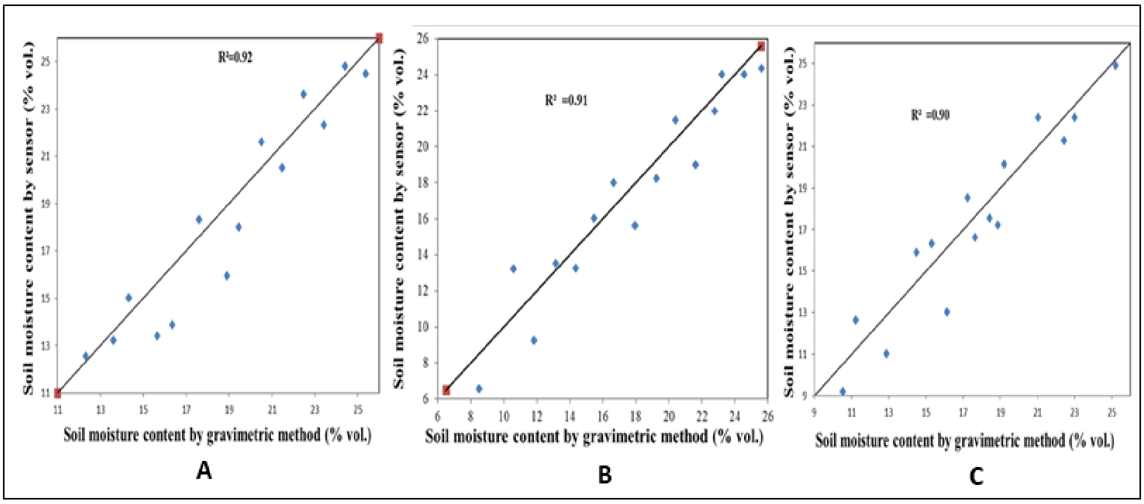

Fig. 5. Relationship between moisture content by sensor and gravimetric method in (A) Sandy loam (B) Loamy sand (C) Silty loam

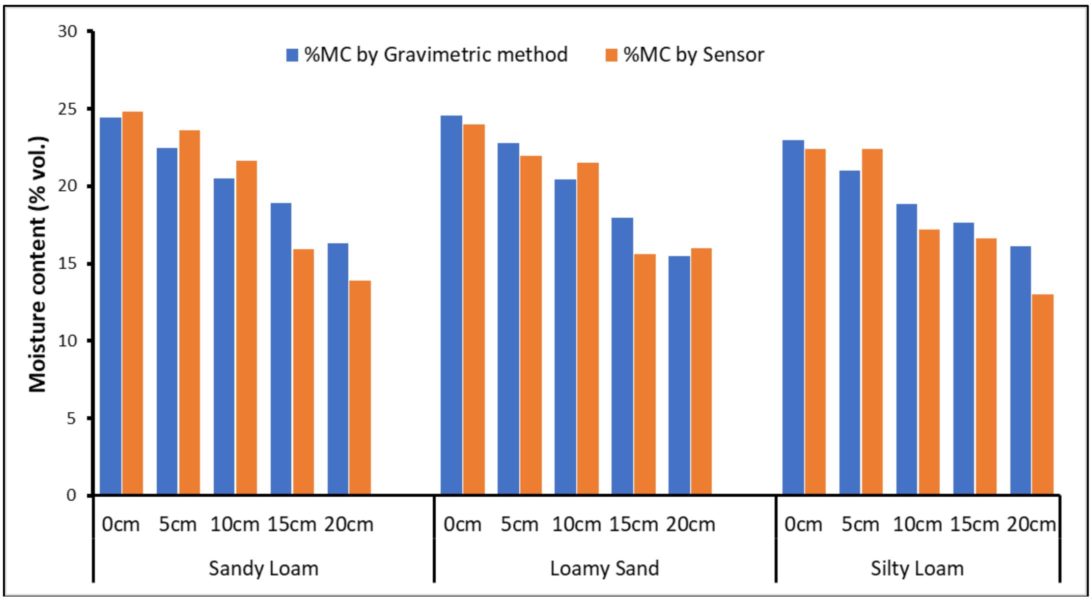

Fig. 6. Comparison of moisture content by both methods at different depths

4. CONCLUSION

A soil moisture sensor, constructed from copper material, was developed, and manufactured, featuring a single probe measuring 300mm in length and 12.5mm in diameter. Calibration of the moisture sensor was performed using the standard gravimetric method, yielding a linear calibration equation. Across three different soil types, RMSE values of 1.02, 1.013, and 1.022 were obtained, indicative of the superior performance of the developed sensor. The Nash-Sutcliffe Efficiency and Coefficient of Determination (R^2) values were found to be 0.90, 0.90, 0.89, and 0.92, 0.91, 0.90, respectively. With a correction factor of ±1.02, the developed soil moisture sensor demonstrated satisfactory performance. Subsequently, an automated module was integrated using Arduino platform programming in conjunction with the developed soil moisture sensor, successfully tested across three different soil types. The resulting automated drip irrigation module, based on the developed sensor, presents a convenient solution for irrigation automation, suitable for application even in deficit irrigation conditions.

ACKNOWLEDGEMENTS

Financial support for this research was graciously provided by College of Agricultural Engineering and Technology, Orissa University of Agriculture and Technology, Bhubaneswar, India.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/115020