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N Uma Maheshwari
M.Tech Student, Department of Soil and Water Conservation Engineering, College of Agricultural Engineering, Professor Jayashankar Telangana State Agricultural University (PJTUA), Kandi, Sangareddy, Telangana, India

Dr. N Hari
Scientist, Department of Soil and Water Conservation Engineering, C-DAT, Professor Jayashankar Telangana State Agricultural University (PJTUA), Rajendranagar, Hyderabad, Telangana, India

Dr. G Manoj Kumar
Professor & University Head, Department of Soil and Water Conservation Engineering, Water Technology Unit, C-NARE, Rajendranagar, Hyderabad, Telangana, India

Dr. MD Latheef Pasha
Principal Scientist & Head, Department of Agronomy, AICRP on IFS Unit, C-NARE, Rajendranagar, Hyderabad, Telangana, India

Dr. KBVN Phanindra
Professor & Head, Department of Civil Engineering, Indian Institute of Technology Hyderabad (IIT Hyderabad), Hyderabad, Telangana, India

Corresponding Author:
N Uma Maheshwari
M.Tech Student, Department of Soil and Water Conservation Engineering, College of Agricultural Engineering, Professor Jayashankar Telangana State Agricultural University (PJTUA), Kandi, Sangareddy, Telangana, India

Development, calibration, and validation of an IoT-based soil moisture monitoring system for real-time monitoring in tomato cultivation

N Uma Maheshwari, N Hari, G Manoj Kumar, MD Latheef Pasha and KBVN Phanindra

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Abstract

Efficient irrigation management is essential for improving crop productivity while ensuring the sustainable use of water resources. This study aimed to develop, calibrate, and validate an Internet of Things (IoT)-based soil moisture monitoring system for real-time precision irrigation in tomato cultivation. The developed system integrated an electrical resistance soil moisture sensor, soil temperature sensor, soil data logger, DCON mobile application, Automatic Weather Station (AWS-1234), and NutriSensX soil analysis system to continuously monitor soil moisture, soil temperature, weather variables, and crop growth under field conditions. Sensor calibration and validation were performed using the standard gravimetric oven-dry method to assess the accuracy and reliability of the developed monitoring system. The calibration model demonstrated excellent agreement between sensor observations and gravimetric measurements, with a coefficient of determination (R^2) of 0.98, correlation coefficient (r) of 0.99, RMSE of 0.85%, MAE of 0.68%, and Nash-Sutcliffe efficiency (NSE) of 0.98. Independent validation further confirmed the robustness of the developed system, producing an R^2 of 0.98, RMSE of 1.32%, MAE of 1.16%, and NSE of 0.98. The developed IoT-based monitoring system enabled continuous real-time monitoring of soil moisture, soil temperature, and weather parameters, providing reliable information for precision irrigation scheduling. Overall, the developed IoT-based soil moisture monitoring system proved to be accurate, reliable, and suitable for precision irrigation management, contributing to improved water-use efficiency and sustainable tomato cultivation.

Keywords: Internet of Things (IoT), precision irrigation, sensor calibration, sensor validation, soil moisture sensor, tomato cultivation

Introduction

Agriculture is undergoing rapid transformation through the adoption of advanced digital technologies that improve productivity, resource-use efficiency and sustainability. Increasing pressure on food production due to population growth, water scarcity, climate variability, labour shortages and rising input costs have highlighted the need for efficient crop management practices. Precision agriculture has emerged as a promising approach that utilizes sensors, information and communication technologies, automation and real-time monitoring systems to optimize agricultural operations and support informed decision-making [1, 3]. Tomato (*Solanum lycopersicum* L.) is one of the most important vegetable crops cultivated worldwide and contributes significantly to human nutrition and agricultural economies. Tomato production is highly sensitive to soil moisture availability, environmental conditions, nutrient status and pest incidence. Improper irrigation scheduling can result in water wastage, nutrient losses, reduced crop growth and lower yields. Therefore, continuous monitoring of soil and environmental parameters is essential for efficient irrigation management and sustainable tomato production [4]. The Internet of Things (IoT) has gained considerable attention in modern agriculture due to its capability to facilitate real-time monitoring and remote management of agricultural systems. IoT-based systems integrate sensors, communication networks, cloud platforms and mobile applications to collect, transmit, store and visualize field data. Soil moisture sensors, soil temperature sensors, weather stations and other monitoring devices enable continuous

observation of crop and environmental conditions, thereby supporting precision agriculture practices. Several studies have demonstrated the effectiveness of IoT technologies in improving irrigation scheduling, reducing water consumption and enhancing crop productivity [2, 3, 5]. Among the various parameters affecting crop growth, soil moisture plays a critical role in determining irrigation requirements and crop performance. Accurate measurement of soil moisture is essential for efficient water management and precision irrigation scheduling. However, sensor-based measurements require proper calibration and validation under field conditions to ensure reliable performance. Calibration of soil moisture sensors using standard gravimetric methods helps establish relationships between sensor readings and actual soil moisture content, thereby improving measurement accuracy and confidence in field applications [6, 8].

Weather monitoring is another important component of precision agriculture. Parameters such as air temperature, relative humidity, rainfall, wind speed and solar radiation significantly influence crop growth, evapotranspiration and irrigation requirements. Automatic Weather Stations (AWS) provide continuous monitoring of environmental conditions and support better understanding of crop-weather interactions. Integration of weather monitoring with soil moisture sensing can facilitate improved irrigation management and resource utilization [9, 10]. Although several IoT-based agricultural monitoring systems have been reported, limited studies have focused on the calibration and field validation of soil moisture sensors integrated with real-time weather monitoring for tomato cultivation under local field conditions. Therefore, the present study was undertaken to develop an IoT-based soil moisture monitoring system and evaluate its calibration and validation for tomato cultivation. The study focused on sensor calibration, validation and real-time monitoring of soil and environmental parameters to support precision irrigation and sustainable tomato

production. Specifically, the objectives were to (i) develop an IoT-based soil moisture monitoring system for real-time monitoring in tomato cultivation; and (ii) calibrate and validate the soil moisture sensor under field conditions using the gravimetric method.

Materials and Methods

Study area

The study was conducted at the College of Agricultural Engineering (CAE) in Kandi, Sangareddy, India (17.63° N, 78.08° E; 516 m AMSL) during the tomato growing season from 13 January 2026 to 4 May 2026 (Fig. 1). The experimental site is situated in the semi-arid tropical region of Telangana and experiences distinct seasonal climatic variations characterized by moderate rainfall, warm summers and mild winters. The experimental field covered an area of approximately 278 m² and was cultivated with tomato (*Solanum lycopersicum* L.) under furrow irrigation. The soil of the experimental site was classified as sandy loam, which is suitable for vegetable crop cultivation due to its favourable drainage and aeration characteristics. The NutriSensX Soil Health Testing Kit was used for the determination of the soil chemical and physical properties of the experimental field. The soil analysis indicated a soil pH of 7.0, electrical conductivity of 0.10 dS/m, organic carbon content of 0.75%, available nitrogen of 17.73 ppm, available phosphorus of 11.40 ppm, and available potassium of 116.90 ppm. Bulk density of 1.22 g/cm³ was obtained from the Soil Health Card generated by the NutriSensX Soil Health Testing System (Fig. 2) after completion of soil analysis. Soil moisture and soil temperature were monitored using the solid-state electrical resistance soil moisture sensor and temperature sensor. The collected soil, weather and crop observations were utilized for evaluating the performance of the developed IoT-based monitoring system under field conditions.

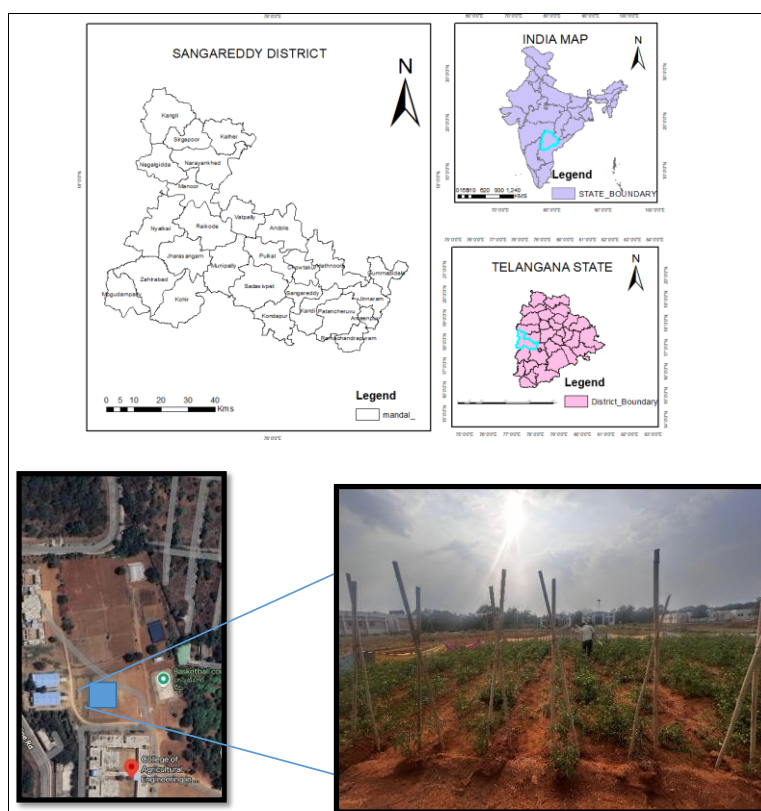


Fig 1: Location map of the study area at the college of agricultural engineering farm, PJTAAU, Kandi, Telangana-India



Fig 2: NutriSensX soil health testing system

Experimental layout and crop management

The experiment was conducted in an open-field environment using a furrow irrigation system. The experimental field covered an area of approximately 278 m² (19.03 m × 14.60 m) and was laid out according to recommended agronomic practices for tomato cultivation. A total of 28 rows were established in the experimental field, with approximately 40 plants accommodated in each row, resulting in about 1120 plants. The crop was planted at a spacing of 45 cm × 90 cm, with a ridge width of 60 cm, furrow width of 30 cm, and ridge height of 20-25 cm. The field layout was designed to facilitate uniform irrigation, crop growth monitoring and sensor installation. Crop management operations including irrigation, fertilizer application, intercultural operations, and weeding, staking and plant protection measures were carried out according to recommended cultivation practices. Soil moisture and environmental conditions were monitored throughout the crop growth period using the installed sensing system.

Development of IoT-based smart sensor system

The IoT-based smart sensor system was developed for continuous monitoring of soil and weather parameters to support precision irrigation and crop management in tomato cultivation. The system comprised an electrical resistance soil moisture sensor, a soil temperature sensor, a soil data logger, the DCON mobile application, an Automatic Weather Station (AWS-1234), a TAGV weather station data logger, and a data acquisition and

communication system. The electrical resistance soil moisture sensor and soil temperature sensor were installed at a depth of 30 cm within the active root zone to continuously monitor soil moisture and soil temperature throughout the crop growth period (Fig. 5). Sensor observations were automatically recorded at 15-minute intervals by the soil data logger and synchronized with the cloud platform for real-time monitoring through the DCON (Fig. 7) mobile application.

Sensor preparation and installation

Prior to field installation, the electrical resistance soil moisture sensor was preconditioned by hydration to ensure proper activation of the porous sensing matrix. The sensors were partially immersed in water for approximately 30 min, followed by air drying. This wetting and drying cycle was repeated before final overnight soaking. The hydrated sensors were installed in vertical auger holes at a depth of 30 cm within the active root zone of tomato plants. A soil slurry prepared from sieved soil and water was introduced into the installation hole to ensure intimate contact between the sensor surface and surrounding soil. The sensors were carefully inserted into the slurry-filled holes (Fig. 3). The remaining space was backfilled and compacted to eliminate air gaps and maintain stable sensor-soil contact for accurate soil moisture measurement. The sensor cables were connected to the data logger, which transmitted soil moisture and soil temperature observations to the cloud platform through LoRa/Wifi communication for real-time monitoring using the DCON mobile application.

The Automatic Weather Station (AWS-1234), installed adjacent to the experimental field, continuously recorded air temperature, relative humidity, rainfall, wind speed, wind direction, atmospheric pressure, latitude, longitude, and altitude as shown in Fig. 6. The recorded weather observations were stored in the TAGV weather station data logger and periodically downloaded using a USB flash drive for further processing and analysis. The integrated database comprising soil moisture, soil temperature, weather parameters, irrigation records, crop growth observations, and yield data was utilized for irrigation scheduling, crop monitoring, and the calibration and validation of the developed sensor system.

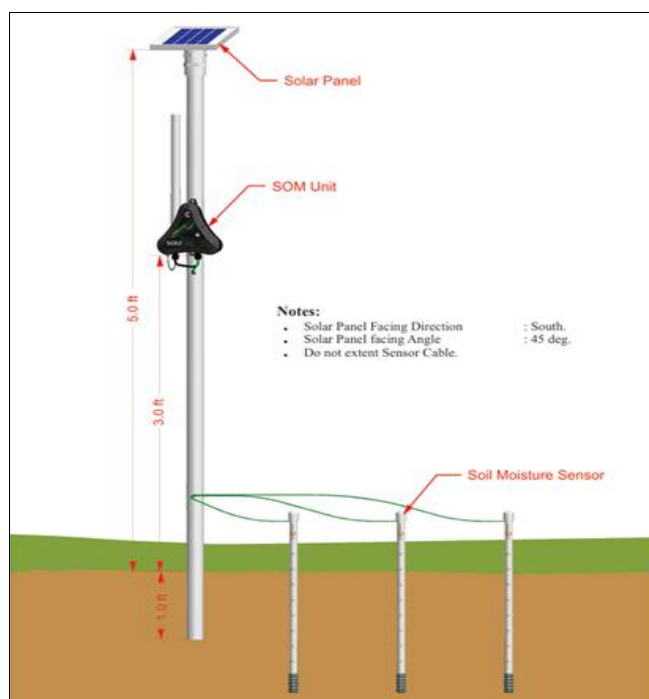


Fig 3: Configuration of the IoT-based soil moisture monitoring system showing the solar-powered data logger, communication unit, and soil moisture sensors installed in the tomato field

The technical specifications of the system are presented in Table 1 ^[11]

Table 1: Technical specifications of the soil moisture monitoring system

Parameter	Specification
Product name	SOM
Power source	9V/6W solar panel
Battery	3.7V/2.6AH rechargeable battery
Battery backup	72 Hours
Communication	LoRa and Bluetooth 5.0
GPS	Inbuilt
Number of soil moisture sensors	1
Number of soil temperature sensors	1

Field Installation Procedure

- A vertical hole was prepared at the selected location for the installation of the 6-inch soil moisture sensor. The hole was extended until the marking corresponding to the sensor

installation depth was level with the soil surface (Fig. 4(a)). In compacted soils, a 7/8-inch OD auger bit attached to a cordless drill or gas-powered auger was used to facilitate hole preparation ^[11].

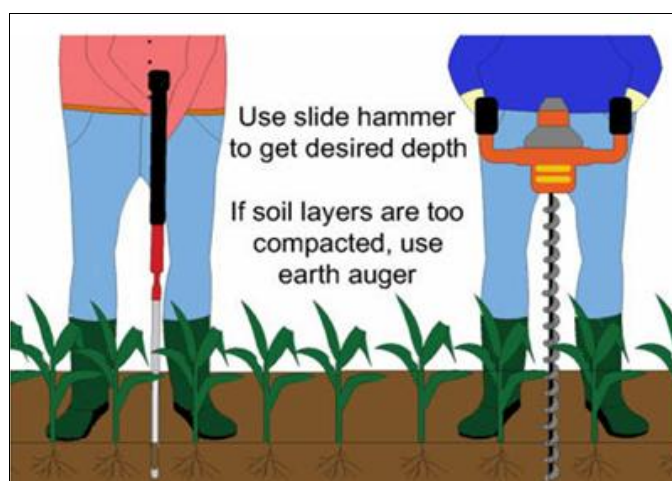


Fig 4 (a): Preparation of soil slurry for sensor installation

A thick soil slurry was prepared by thoroughly mixing sieved soil with preconditioning water to obtain a smooth and uniform consistency. The slurry Fig. 4(b) was then poured into the

installation hole until approximately half of the hole was filled, thereby ensuring proper contact between the sensor and the surrounding soil ^[11].

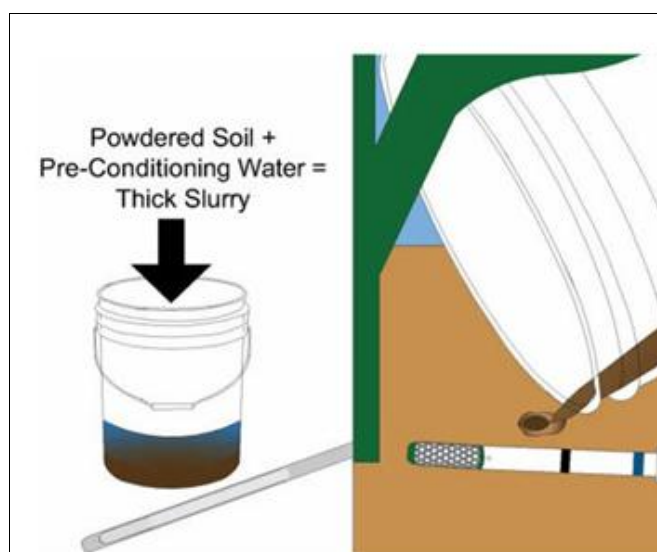


Fig 4 (b): Application of soil slurry before sensor placement

The soil moisture sensor was carefully inserted into the slurry-filled hole until the bottom of the black electrical tape was level with the soil surface Fig. 4(c). Excess slurry displaced during insertion was allowed to flow out naturally. The surrounding soil

was then compacted, and additional soil was mounded around the installation point while securing the rubber washer (where applicable) to minimize water leakage into the hole and maintain stable sensor-soil contact¹¹.



Fig 4 (c): Installed electrical resistance soil moisture sensor in the field

Soil Moisture Measurements and Sensor Calibration

An electrical resistance soil moisture sensor was calibrated and validated under field conditions to evaluate its accuracy and reliability for real-time soil moisture monitoring in tomato cultivation. The sensor was installed at a depth of 30 cm within the active root zone, and soil moisture observations were recorded at 15-min intervals using the soil data logger and DCON mobile application throughout the calibration period. Soil samples were collected from locations adjacent to the installed sensor between 28 January to 4 February 2026 at 09:00, 14:00, and 18:00 h to capture variations in soil moisture under different environmental and irrigation conditions.

Gravimetric soil moisture content was determined using the standard oven-drying method. Fresh soil samples were weighed immediately after collection and dried in a hot air oven at $105 \pm$

2°C for 24 h until a constant weight was attained. The gravimetric moisture content was calculated from the difference between the wet and oven-dry soil weights and used as the reference soil moisture value. Standard procedures were followed for the determination of gravimetric soil moisture content^[12].

The gravimetric soil moisture values were compared with the corresponding readings obtained from the electrical resistance soil moisture sensor. A linear regression model was developed to establish the calibration relationship between sensor readings and gravimetric soil moisture content. The developed calibration equation was subsequently validated using an independent dataset collected under different field moisture conditions to assess the accuracy, reliability, and suitability of the sensor for real-time soil moisture monitoring in tomato cultivation.



Fig 5: Soil moisture and temperature sensor



Fig 6: IMD Automatic Weather Station (AWS-1234)

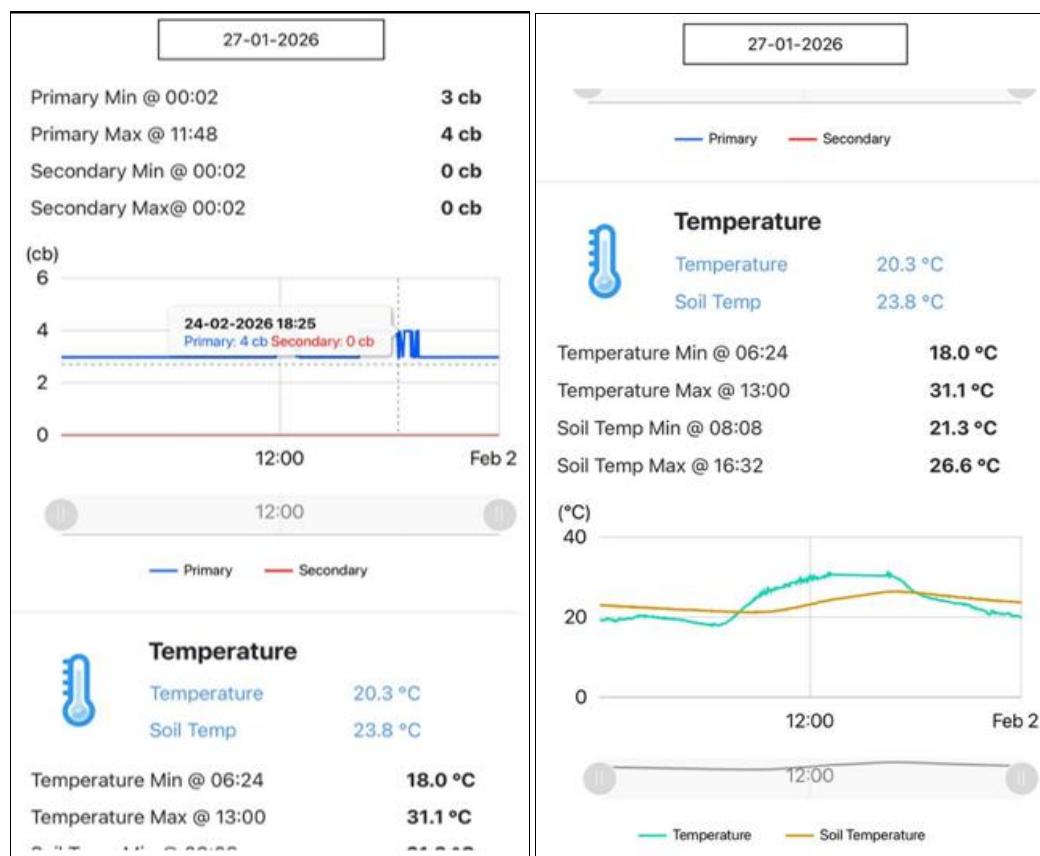


Fig 7: Real-time soil moisture and soil temperature monitoring through the DCON application

Soil moisture sensor validation

The calibrated soil moisture sensor was validated using an independent dataset collected under field conditions. Sensor readings were compared with soil moisture content determined using the standard gravimetric oven-dry method. The objective of validation was to assess the accuracy and reliability of the developed calibration equation under conditions different from those used during calibration. Soil samples were collected from locations adjacent to the installed sensor and analyzed using the gravimetric oven-dry method to determine actual soil moisture content. Simultaneously, soil moisture observations were recorded from the sensor through the DCON mobile application. The calibrated equation developed during the calibration stage was applied to estimate soil moisture content from sensor measurements. The observed and predicted soil moisture values were compared using statistical performance indicators to evaluate the predictive capability of the calibrated sensor. The validation process was carried out to determine the suitability of the sensor for continuous soil moisture monitoring and irrigation management under field conditions.

Gravimetric moisture content (oven dry method)

$$MC_g = \frac{W_w - W_d}{W_d} \times 100 \quad (1)$$

Where:

- MC_g = Gravimetric moisture content (%)
- W_w = Wet soil weight (g)
- W_d = Oven dry soil weight (g)

Results and discussion

Soil moisture sensor calibration

The performance of the electrical resistance soil moisture sensor was evaluated by comparing sensor-measured soil moisture content with gravimetrically determined soil moisture values. The calibration relationship between observed and sensor-predicted soil moisture is presented in Fig 8. A strong positive linear relationship was observed between the gravimetric soil moisture content and sensor measurements. The calibration equation obtained was:

$$Y = -0.61 + 1.028X \quad (2)$$

Where:

Y = observed gravimetric soil moisture content (%)

X = sensor-measured soil moisture content (%).

The coefficient of determination (R^2) obtained during calibration was 0.98, indicating that approximately 98% of the variation in gravimetric soil moisture was explained by the sensor observations. The correlation coefficient ($r = 0.99$) further confirmed the strong agreement between the two measurement methods. The calibration model produced low error values with RMSE and MAE of 0.85% and 0.68%, respectively, indicating high measurement accuracy. The bias value was negligible (0.00), suggesting the absence of systematic overestimation or underestimation by the sensor.

The Nash-Sutcliffe Efficiency (NSE) value of 0.98 demonstrated excellent predictive performance of the calibration model. The highly significant p-value (1.19×10^{-10}) indicated that the observed relationship between sensor readings and gravimetric measurements was statistically significant.

These results demonstrate that the electrical resistance soil moisture sensor provided reliable and accurate measurements under field conditions and can be effectively utilized for continuous soil moisture monitoring and irrigation management in tomato cultivation. The high calibration accuracy obtained in the present study is comparable with previous investigations on soil moisture sensor calibration⁸ reported that proper calibration substantially improves the accuracy and reliability of low-cost soil moisture sensors under field conditions, thereby reducing measurement uncertainty. Similarly⁵, highlighted that the integration of calibrated soil moisture sensors with IoT-based monitoring systems enables reliable real-time data acquisition for precision irrigation applications. The coefficient of determination ($R^2 = 0.98$) and the very low error statistics (RMSE = 0.85% and MAE = 0.68%) obtained in the present study are consistent with these findings, indicating that the developed monitoring system can provide dependable soil moisture information for irrigation scheduling and precision water management in tomato cultivation.

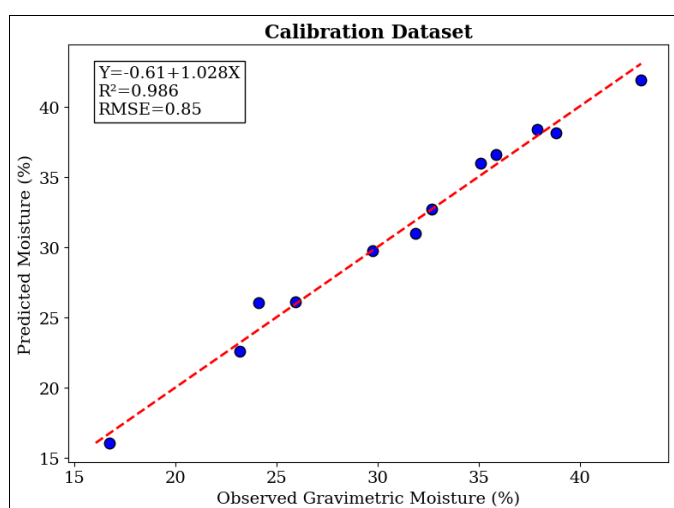


Fig 8: Calibration relationship between observed gravimetric soil moisture and sensor-predicted soil moisture content

Soil moisture sensor validation

The performance of the calibrated soil moisture sensor was further evaluated using an independent validation dataset collected under field conditions. Sensor-predicted soil moisture values were compared with gravimetrically determined soil moisture content to assess the reliability and accuracy of the developed calibration model. The relationship between observed and sensor-predicted soil moisture content during validation is presented in Fig. 9. The validation results demonstrated excellent agreement between sensor observations and reference gravimetric measurements. The coefficient of determination (R^2) during validation was 0.98, indicating that the calibrated sensor successfully explained 98% of the variability in soil moisture content. The correlation coefficient ($r = 0.99$) confirmed a strong positive relationship between observed and predicted values. The validation model exhibited low prediction errors with RMSE and MAE values of 1.32% and 1.16%, respectively. The bias value was 0.78, indicating only a minor deviation between observed and predicted soil moisture values. Furthermore, the Nash-Sutcliffe Efficiency (NSE) value of 0.98 indicated excellent predictive capability and high model reliability. The obtained p-value (2.27×10^{-5}) confirmed that the relationship between sensor measurements and gravimetric observations was statistically significant.

The validation results confirmed the robustness and reliability of the calibrated soil moisture sensor for field applications. The excellent agreement between observed and predicted soil moisture values demonstrates that the developed calibration equation can accurately estimate soil moisture under varying field conditions. Similar observations have been reported by⁵, who emphasized that IoT-enabled sensing systems provide reliable real-time monitoring for precision agriculture when supported by accurate sensor calibration. Likewise^[8], reported that field-calibrated soil moisture sensors exhibit improved predictive performance and can effectively support irrigation management decisions. The validation statistics obtained in the present study ($R^2 = 0.98$, NSE = 0.98, RMSE = 1.32%, and MAE = 1.16%) demonstrate performance comparable with these published studies, confirming that the developed IoT-based monitoring system provides accurate, reliable, and stable soil moisture estimation. Therefore, the calibrated sensor is suitable for continuous soil moisture monitoring, irrigation scheduling, and precision water management in tomato cultivation.

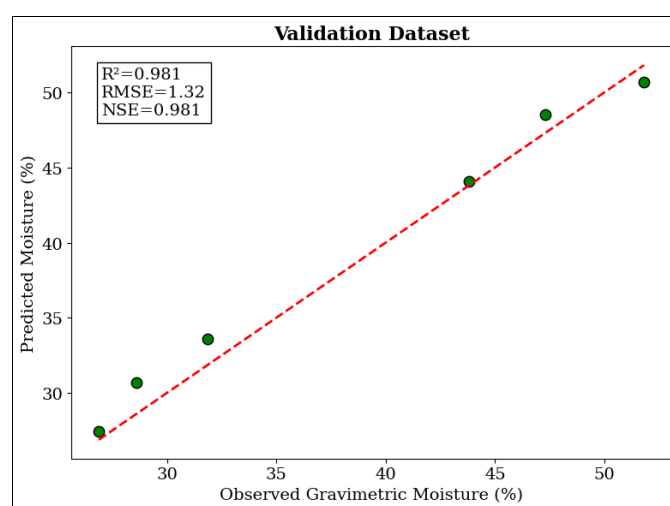


Fig 9: Relationship between observed gravimetric soil moisture content and sensor-predicted soil moisture content during validation

Conclusion

An IoT-based soil moisture monitoring system was successfully developed and evaluated for real-time monitoring in tomato cultivation. The integrated system comprised an electrical resistance soil moisture sensor, a soil temperature sensor, a data logger, the DCON mobile application, an Automatic Weather Station (AWS-1234), and the NutriSensX soil analysis system, enabling continuous acquisition and visualization of soil and weather data under field conditions. Calibration of the soil moisture sensor using the standard gravimetric oven-dry method established a strong relationship between sensor readings and reference measurements, achieving a coefficient of determination (R^2) of 0.98, RMSE of 0.85%, MAE of 0.68%, and NSE of 0.98. Independent validation further confirmed the reliability and predictive capability of the system with an R^2 of 0.98, RMSE of 1.32%, MAE of 1.16%, and NSE of 0.98. These results demonstrate that the proposed monitoring system provides accurate and reliable soil moisture measurements, making it suitable for real-time irrigation management. The integration of IoT technologies with field-based sensing offers a practical and cost-effective solution for continuous monitoring, improved irrigation scheduling, and efficient water resource management. The proposed system has significant potential to support precision agriculture and promoting sustainable tomato cultivation, particularly under conditions where timely and accurate soil moisture information is essential for decision-making.

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