Development, Calibration, and Field Validation of an Internet of Things Based Real-Time Smart Soil Moisture Monitoring System Using Capacitive Soil Moisture Sensors

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Abstract. IoT-based precision irrigation optimizes agricultural practices by using real-time sensor data to automate irrigation systems. Unlike traditional, labor-intensive irrigation systems that waste time, energy, and water, modern sensor-driven systems enhance efficiency, conserving resources and increasing food production. This research presents the development, calibration, and field validation of an internet of things (IoT) based soil moisture monitoring system using capacitive soil moisture sensors. The system comprises several nodes installed in a series that are connected to a cloud server (central controller) via Wi-Fi/LORA (Long Range) module. Each node consists of an array of capacitive soil moisture sensors; Arduino-based microcontroller, power supply, and Wi-Fi/LORA module. Soil moisture sensors were calibrated with field soil and then installed in the field in the form of a vertical array. The sensors monitor soil moisture fluctuations at various depths within the crop's root zone, microcontroller performs actions to maintain the required soil moisture dynamics and transmits the sensors data to the transceiver. The Wi-Fi/LORA module transfers data to the cloud server at a specified frequency i.e. 60 sec/cycle. Then data can then be accessed via a mobile phone application "BLYNK" which provides a Digital & Graphical User Interface for the real-time monitoring and regulating of water supply to the crops. The system provides an economical solution for real-time soil moisture monitoring in the root zone, keeping users informed about moisture levels. It can be deployed across irrigation fields to optimize water and energy use while maximizing crop yields.

Keywords: Irrigation water management, smart irrigation system, irrigation scheduling, sensors calibration, soil moisture monitoring, internet of things, precision agriculture, water-energy-food nexus.

1 Introduction

Agriculture is vital to Pakistan's socio-economic development. Being one of the largest sectors agriculture 24% to GDP and is the major source of food in Pakistan. [1] Irrigation is an important process in agriculture that has great impact on crop production. Agriculture the biggest user of freshwater resources, consuming around 70% of annual water withdrawal worldwide [2]. Globally, Pakistan ranks as the fourth-largest consumer of groundwater and holds the top position in groundwater extraction

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for irrigation purposes [3]. Surface water resources of Pakistan are capable of irrigating only 27% of the country's cultivable land, the remaining 73% relies directly or indirectly on groundwater for irrigation [4]. It is also estimated that about40% of agricultural freshwater is lost in developing countries due to evaporation, surface runoff, and deep percolation below the root zone [5]. Pakistan currently has a Water Resources Vulnerability Index (WRVI) of 77%, indicating severe water scarcity conditions [6]. The situation is further worsened by the current climate changes and erratic weather patterns that have badly affected Pakistan during the last decades. Therefore, the country's water resources are declining, and glaciers are melting at an unprecedented rate. Owing to below-average reservoir levels due to which water availability for irrigation and environmental flows has decreased appreciably [7].

Water management in agriculture is now recognized broadly as a significant challenge which frequently attached to growth issues [8]. Agricultural activity has degraded many freshwater resources, resulting in salinization, over-exploitation, and nutrient contamination. Many studies on irrigation water requirements have been conducted [9]. Irrigation is the controlled artificial supply of water to land to support plant growth and enhance agricultural productivity [10]. It is critical to determine the water requirements of crops to improve irrigation scheduling [11]. Therefore, a solution is required for determining field soil moisture dynamics, so that the crops can be irrigated according to their water requirements.

With technological advancements, the designing of such a system is now possible which can help farmers to minimize the water losses irrigation [12]. New methods of smart irrigation systems use soil moisture sensors for gathering real-time soil moisture data can accurately monitor the status of soil moisture dynamics. The use of comparatively low-cost sensors allows affordability and instantaneous monitoring of soil moisture dynamics in fields [13].

Over time, different methods of irrigation have been developed to satisfy the irrigation water needs of specific crops in specific regions. Surface, subsurface, sprinkler, and drip/micro irrigation are the four main methods of irrigation [14] as shown in Fig.1 and Table 1.

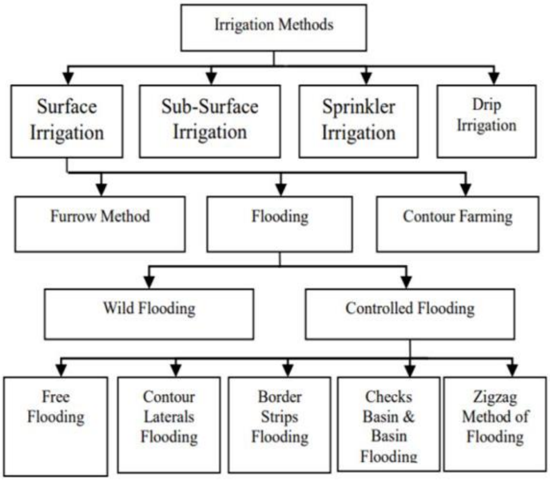

Fig. 1. Different Methods used for irrigation

Table 1. Typical *application efficiencies of different Irrigation Systems* [15]

Irrigation methods	Application efficiency
Surface irrigation	
Level basin	60-80 %
Border	60-75 %
Furrow	50-70 %
Drip irrigation	80-90 %
Sprinkler irrigation	60-85 %
Sub-surface irrigation	50-80%

No irrigation method is perfectly suitable for very soil types, meteorological conditions and a wide range of crop cultures while also providing 100 percent efficiency [16]. Various soil types may show dielectrically different properties [17]

Various procedures and apparatus are used for the determination soil moisture; they are classified in two categories i.e modern/advanced and classical methods [18]. Thermogravimetric method is a classical method of soil moisture determination and is used as a standard reference [19]. Though, this procedure is more time taking, laborious, and destructive to the soil [20]. The second method is the use of calcium carbide, in this method soil moisture content is calculated from the pressure produced due to reaction between soil water and calcium carbide [21]. Another classical method is the estimation of soil moisture through appearance and feel of soil this method is totally dependent on the farmer's experience [22]. Advanced methods of detecting soil moisture are using a mixture of sensors and other devices [23]. Like tensiometer which measures soil moisture using a sealed tube with a ceramic tip. When the soil suck water from the tube through the porous ceramic tip a vacuum is created inside the tube which is measured by a gauge near the top of the tensiometer [24], [25]. They have a very low range of measurements even though are easy to use [26]. Another advance method of soil moisture measurement is Neutron scattering method [27]. This correlates soil moisture with the proportion of the neutron slowed down by the hydrogen atoms of water present in the soil[28], [29]. Furthermore, soil resistivity methods are also used for measuring soil moisture. This method is low cost, and easy but careful calibration is required and soil salinity care influence the values [30]. Its working on the principle of determining either resistivity of the material that is in equilibrium with the soil or the resistivity between two electrodes placed in the soil [31]

Despite multiple methods have developed. Among all Frequency Domain Reflectometry (FDR), Time Domain Reflectometry (TDR), and capacitance sensor are more popular due to their on-site measurements, automation ability, high accuracy, and easy installation [32]. Capacitance sensors are frequently prioritized upon TDR and FDR, due to their low cost, less energy requirements, and real-time soil moisture monitoring [33]. These are commonly used methods in precision agriculture, and different soil properties, careful calibration, experience of the user can highly influence the accuracy of these methods [34].

Accurate estimation of the soil moisture content can support multiple fields for instance hydraulics, agronomy, and soil morphology physics [35]. Soil physical, chemical, mineralogical, and biologic properties are highly influenced by it [36]. Soil moisture plays a vital role in the climate system, by controlling the energy flow between the earth's surface and atmosphere. Thus monitoring of soil moisture spatial and temporal variability is crucial [37]. In precision agriculture continuous soil moisture monitoring is receiving more attention. Since it plays a major role in plant/crop growth and development, irrigation scheduling, soil drainage, evapotranspiration, and tillage operations, among other processes [38].

To enhance irrigation efficiency, new techniques of smart and intelligent irrigation systems are developing at a rapid pace. These systems helps in minimizing water losses at the irrigation fields and has higher efficiency for irrigation [39]. This research focusses on the development of a smart soil moisture monitoring system based on IoT using an array of four capacitive sensors for soil moisture detection at various depths within the plant's root zone. The capacitive soil moisture sensors sense the moisture level of the soil and are an interface with the Arduino Uno ESP32 microcontroller. Using the WI-FI/LORA module, the real-time data of the field soil moisture is received in a BLYNK mobile application in graphical format. Deep percolation of irrigation water below the root zone can be minimized by monitoring soil moisture variation at the crop's root zone, and the irrigation schedule can be managed [40].

Generally, farmers apply over irrigate the crops due to lack of soil moisture monitoring technology, lack of awareness about crop water requirements, and irrigation scheduling. This this increases water losses, energy consumption for water pumping and decreases crops yield an soil fertility [41]. The developed system can help to reduce water & energy consumption and increase crop production. All these features make this research a promising approach for enhancing agricultural and irrigation efficiency.

2 Literature Review

Pakistan's economy is largely driven by agriculture with almost 47% of its population directly or indirectly involved in the agricultural sector [42]. Due to this high dependency on agriculture, Pakistani farmers cultivate an area of 21.2 M hectares, of which approximately 80% is irrigated. As a result 93% of the total water in Pakistan is used for irrigation purposes [43]. By 2025, Pakistan may experience a deficit of 31 million acre-feet (MAF) of water, which could pose a severe threat to the country's economy. [44].

In 2009 Italian Researcher Alberto Pardossi introduced the concept of installing sensors in different root zones to monitor and control the flow of water as per the moisture conditions of the soil. This article suggests a way of choosing and installing moisture sensors based on the following attributes: range of measurements, accuracy, frequency of data, data transfer mechanism and handling, maintenance, compatibility and cost [45]. In the early prototypes of smart irrigation models, moisture detecting sensors were programmed with a timer which worked like a relay system. The flow of water starts to a crop when the sensor detects low volumes of moisture in the soil and the timer automatically shuts down the flow after a specific programmed time. This system resulted in the 47% more usage of water than its adversary sprinklers or drip irrigation systems [46].

Due to the high amount of losses and irregularities in the digital/manually operated irrigation systems, researchers further tried to develop an automatically programmed irrigation system which can detect, regulate and monitor the flow of water to the crops using a computer (PC) based National Instrument (NI) LabVIEW system, NI myRIO (a micro controller), IOT, GSM (Global System for Mobile Communications), [47] and an automatic water inlet system that also monitors and records temperature, humidity, and sunlight. This system is continuously adjusted and can be controlled in the future to optimize these resources, thereby maximizing plant growth and yield. The system sends an automatic notification to the farmer when the moisture level in the field is low. The information from this system can be obtained via computer software LabVIEW [48].

The PC based systems were costly and far too complex to be operated by an ordinary farmer therefore researchers tried to shift the system to a cloud server which can be conveniently accessed remotely. The Cloud based smart irrigation system consisted of WSN (Wireless Sensor Network), Microcontroller, ZigBee transceivers, GPRS (General Packet Radio Services) packet transmission, and Raspberry Pi [49]. The cloud-based systems were more accurate and cost effective. The circuit can also be fitted with temperature sensors, Infrared sensors (PIR), LED lights and an LCD interface. This system can be operated manually via mobile phone application or programmed to switch ON/OFF automatically as per the requirement of the crops [50].

Arduino is an open-source electronics platform that relies on user-friendly hardware and software. [51]. The wireless sensors network linked to the arduino board collects data from the soil humidity sensors, analyze it according to the programm threshold values and send the data to the transceiver (ZigBee) which can then transfer that data to the cloud server by using Wi-Fi module (ESP1082197). Then the server can be accessed through a cell phone app designed in Linux programming language [52]. PV (photovoltaic) panels can be added to the sensor unit. When exposed to sunlight, each solar cell in the panel consists of two or more precisely crafted layers of semiconducting material (typically silicon) that generate direct current (DC) [53]. The DC current is collected by the wiring in the panel. Using an inverter, this DC current is transformed into alternating current (AC), which is then utilized to power the sensor. These solar panels make the WSNs' power supply self-sufficient [54].

3 Materials and Methods

The methodology implemented in this research comprises of three stages as shown in Fig. 2. These stages include the selection of field for crop production, characterization of the field soil, calibrating capacitive soil moisture sensors according to the properties of field soil, installation of the experimental system in the field for measurements, the monitoring of the real-time soil moisture dynamics, and assessment of water as per the requirements of the crop.

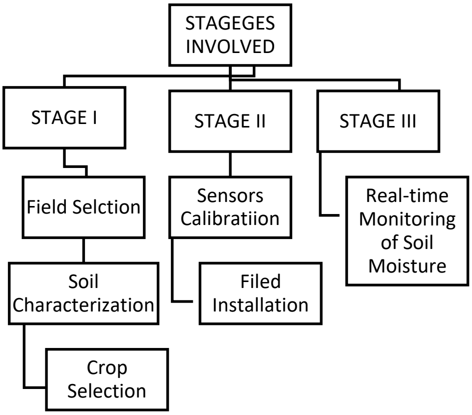

Fig. 2. Project flowchart

3.1 Field Selection and Soil Characterization

The first stage of this research was the selection of a suitable site for which a field near CIRBS Labs at IIU, Islamabad, was selected. The soil of the field has been tested in the geotechnical lab for soil characterization. The characterization of soil includes the type and permeability of the soil for which the samples have been taken from 20cm and 50cm depths to check for texture heterogeneity.

For the grain size analysis, a 500-gm soil sample was taken from the field soil. The tests performed included grain size analysis, Atterberg's limits, and hydraulic conductivity tests. The grain size analysis test was conducted according to the AASHTO DESIGNATION: T27-99, ASTM DESIGNATION: C 136-96 a standard method while the Unified Soil Classification System (USCS) was used to find Atterberg's limits. Based on the grainsize analysis (Table 2) and Atterberg's limits, the soil type was found Lean Clay with Sand.

Table 2. Particle size analysis of field soil sample

Sieve No	Size (mm)	Soil Retained	Cumulative Mass Retaine	% Mass Retained	% Passing
4	4.750	11.8	11.80	2.360	97.64
10	2.000	20.6	32.40	6.480	93.52
40	0.430	57.8	90.20	18.04	81.96
60	0.250	61.7	151.9	30.38	69.62
100	0.150	70.0	221.9	44.38	55.62
200	0.075	26.2	248.1	49.62	50.38
pan	0.000	250.5	498.6	0.000	0.000

After the classification of field soil, the hydraulic conductivity test was performed to know the drainage properties of the soil, Soil permeability, or hydraulic conductivity, is assessed using various methods, including constant and falling head laboratory tests on intact or reconstituted samples and In-situ borehole permeability testing [55] and field pumping tests can also be used to determine permeability in the field. As the field soil type is already known (Lean clay with sand). Therefore, the falling head test was conducted to determine the soil's drainage properties. Agricultural decisions heavily rely on soil hydraulic conductivity to determine nutrient leaching, predict erosion, or assess irrigation rates.

The average value of the permeability coefficients was found to be $8.96x10^{-6}$ cm/sec or $8.96x10^{-8}$ m/sec of the three trails, which shows a very low permeability rate. The values of permeability coefficient for clayey soil are less than $1x10^{-7}$ m/sec. Therefore, the permeability values of the tested soil samples resemble clayey soils.

3.2 Calibration of Capacitive Soil Moisture Sensors

A sensor is an instrument that senses and measures physical quantities like temperature, moisture, and PH in the surrounding and converts it into a digital signal [56]. The sensors used here for the calibration procedure and analysis are same as used by [57]. The sensor utilized incorporates a 555-timer integrated circuit to convert its resonance frequency into an analog signal, which is then processed by an Arduino board. This analog signal is calibrated to establish an empirical correlation between soil moisture and the sensor's output signal. The Arduino board employed is an Arduino Uno, featuring a 10-bit ADC that operates at 3.3V using an external reference. The capacitive sensor functions at 3.3V but is effective only within the range of approximately 1.5V to 3.3V. The components used in this setup include a Capacitive Soil Moisture Sensor, an Arduino Uno Board, and a High-Resolution Digital Scale.

Varied amounts of water were added to air-dried soil samples. Then the samples were placed in different containers and the voltage readings from the capacitive soil moisture sensor were recorded at the respective moisture content as shown in Table 3. A little part of the soil was then taken from each container to find the moisture content by gravimetric method. After finding the moisture content of all the soil samples, a calibration graph was drawn between MC% and the inverse of the respective voltage values as shown in Fig. 3. This provides a relationship for detecting any moisture in the field.

Table 3. Voltage values from sensors for different moisture contents %

Soil Sample	Moisture Content (%)	Voltage (V)	1/Voltage
1	0.00	2.75	0.363636
2	2.80	2.28	0.438596
3	7.90	1.88	0.531915
4	11.8	1.64	0.609756
5	17.3	1.44	0.694444
6	21.8	1.34	0.746269
7	28.1	1.28	0.781250
8	33.4	1.25	0.800000
9	38.7	1.24	0.806452
10	42.8	1.23	0.813008

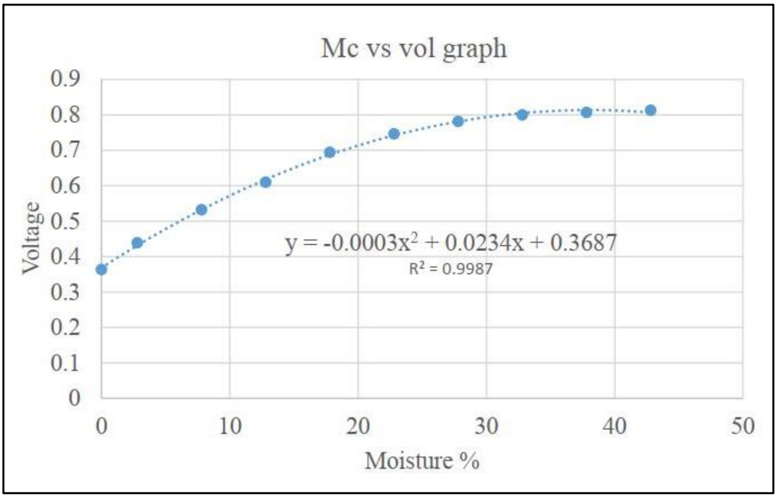

Fig. 3. Graph between moisture content % and voltage values

3.3 Installation of Final Experimental Setup in The Field

The Arduino was reprogrammed according to the calibration curve for finding soil moisture content at the selected field. Then the system was redesigned for permanent setup at the field and was linked with the LORA module. The final design of the experimental setup is shown in Fig. 4. Separate programming was done for the NodeMCU ESP32 LORA transmitter and receiver. The transmitter receives the data of all the four capacitive soil moisture sensors and sends it to the receiver, which is fixed at and connected to WI-FI situated about 2km from the field. After receiving the data signals from the field, the receiver sends the data to the cloud server which is then received through a mobile app "BLYNK". The mobile application shows the data of all four sensors in a graphical format in different colors for identification purposes.

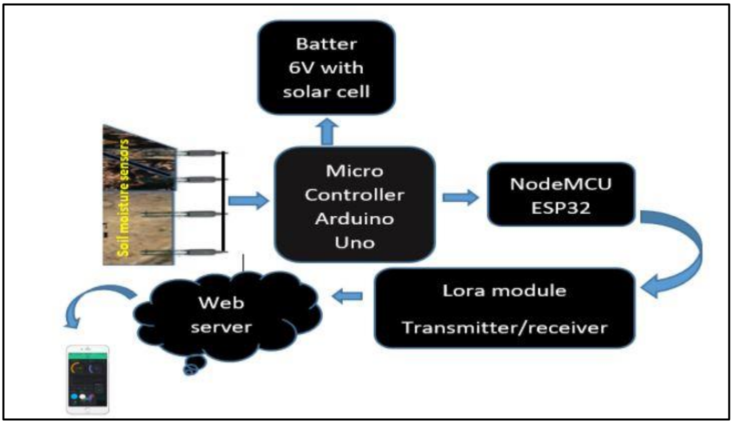

Fig. 4. Mechanical design of the system

For the field installation of setup, about a 2 ft deep borehole was made in the field soil for sensors installation. Keeping in mind the root depth array of four capacitive soil moisture sensors were installed at different depths [6, 12, 18, and 24] inches. A solar-powered IoT-based control unit was then installed with the sensors.

4 Results and Discussions

The soil moisture data was recorded and monitored for the plant in a mobile application "BLYNK" in a graphical format as well as individual data of each sensor in CSV format. The application also shows the battery level of the setup. It is an open-source mobile application designed for IOT. The field data of sensors was displayed and stored by the application. A new project was created in BLYNK, and its necessary widgets were added to show the soil moisture data. Live data of the sensors is shown in Fig. 5. The WI-FI/ LoRa receiver receives field data through a LoRa transmitter and is pushed to the BLYNK server which is then displayed in the mobile App.

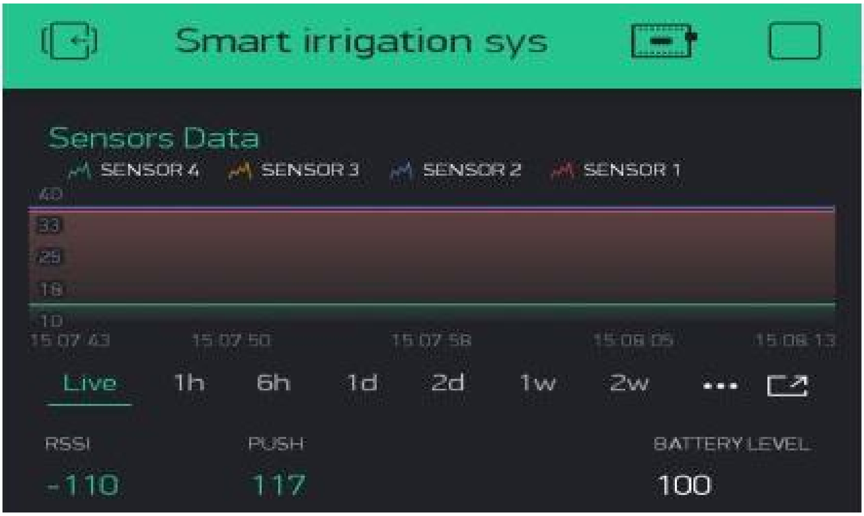

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Fig. 5. Live soil moisture data of the sensor at different depths at the field.

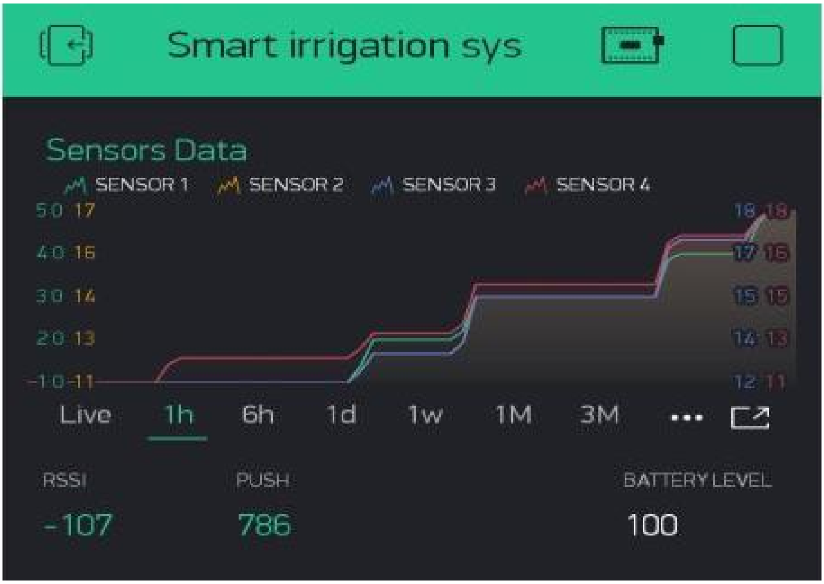

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Fig. 6. Real-time soil moisture data at various depths within the root zone

The line graph in Fig. 6. shows live data of the soil moisture at various depths within the plant's root zone. Four sensors Sensor-1, Sensor-2, Sensor-3, and Sensor-4 were installed at depths of 6, 12, 18, and 24 inches respectively from the earth surface. Different colors were selected for each sensor to differentiate data in graphical format. Sensor 1 data is shown by red color, sensor 2 by blue, sensor 3 by yellow, and sensor 4 by green. The X-axis shows the time in hours, days, and months and the Y-axis shows the moisture quantity of all the four sensors at the aforesaid depths. After irrigation the sensors show the variation of moisture at their depth position in the root zone.

During the irrigation, as the water reaches the top sensor (sensor 1), it shows an increase in the graph. After some time, the moisture reaches sensor-2, and its graph goes up. Similarly, sensor-3 and sensor-4 show an increase in moisture at their respective depths. Before the irrigation, sensor-1 shows a moisture value of 11%, sensor-2 shows 12%, sensor-3 shows 11% and sensor-4 shows 10%. While after receiving water during irrigation, the moisture values of all the four sensors at different depths starts increasing and shows the values of 38% by sensor-1, 38% by sensor-2, 36% by sensor-3 and 28% by sensor-4. When the moisture percentage becomes less than 10 at the first depth, means the plant is dry and needs to be irrigated. Field soil moisture data was recorded for 17 days. During these days, the field is irrigated only once because it was a rainy season. For better understanding, we downloaded data from the BLYNK server in a CSV file format to the linked email address. The data of all four sensors were gathered in a single Excel spreadsheet and analyzed for the trends.

As the system pushes the sensor readings to the BLYNK server at every one-minute interval, the thousands of readings are analyzed into two graphs for ease. After growing the plants on 19 July, irrigation was applied to the field that day and moisture data started storing in the BLYNK app. The graph in Fig. 7. shows that on 19 July minimum moisture was recorded by sensors at their respective depths which were 14.5%, 12%, 11%, and 10.5%. When irrigation is applied, the values of the sensors go to a maximum of 42%, 36%, 32%, and 28% respectively. After 19 July, no irrigation was applied and the moisture values at the depths are going on decreasing from the surface to the bottom of the plant's root zone. On 25 July the field received heavy rain and again the sensors gained high values of moisture contents.

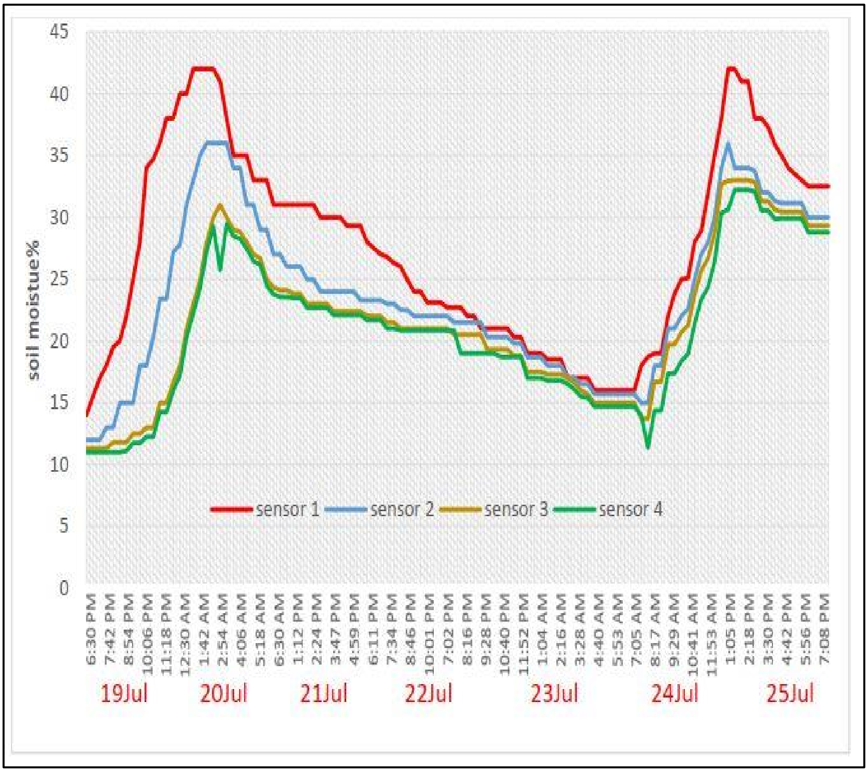

Fig. 7. Soil moisture data for the first seven days.

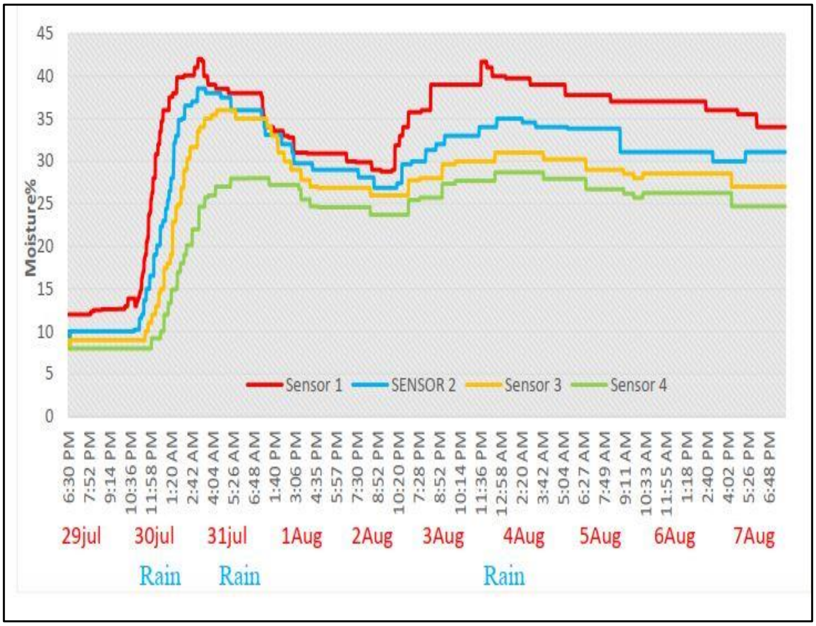

Fig. 8. Field soil moisture data from 29-July to 7-Aug.

Fig. 8. shows, the data recorded from 29-July to 7-Aug. During this period, no irrigation is provided to the field and all the moisture is due to rain. The field received rain on 30 and 31-July, and 4-Aug. The trends of soil moisture at different depths show a clear increase these days. The field didn't receive any irrigation during this period (29Jul - 7Aug) and the required moisture was maintained due to rain.

5 Conclusion and recommendations

It is concluded that the implementation of capacitive soil moisture sensors, their meticulous calibration, and the establishment of a smart soil moisture monitoring system have proven to be very effective in monitoring soil moisture dynamics efficiently. The system demonstrated stability and accuracy in providing real-time data, capturing irrigation events and soil moisture fluctuations with precision. The integration of the BLYNK mobile app and solar-powered components further enhances its reliability, allowing continuous monitoring and easy data access. Explore further automation by integrating a solenoid valve and programming the system to automatically adjust irrigation based on pre-set moisture thresholds, enhancing water use efficiency. Collaboration with stakeholders is required to promote widespread adoption of this smart soil moisture monitoring system, for enhancing sustainable water and energy practices in agriculture.

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7 Disclosure of Interests

The authors declare that there are no conflicts of interest pertinent to this paper. The work presented in this manuscript has not been influenced by any financial, personal, or professional interests.

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