Review Article

Efficiently Estimating Soil Moisture Content: Adopting IoT Technologies

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Abstract: Soil moisture plays a major role in agricultural yield, hydrological, and environmental monitoring studies. Soil-moisture's accurate estimation is important for successfully improving crop yield efficiently using agricultural resources and effectively managing water resources. The current article aims to list different approaches to estimating soil moisture such as using microwave, radar, and sensor-based methods of electronic and communication engineering and also IoT-based methods from computer engineering fields to find the journey of use of state-of-the-art technology methods for measuring soil moisture. Out of the mentioned methods, the Sensor & IoT-based method is playing a vital role and is currently being used in advanced countries. Therefore this research is focused on experimenting the water flow control and measurement of soil moisture using sensors on micro-controller-based prototypes. Experiments showed that it is feasible to estimate the requirement of water more accurately than traditional methods. Thus more water savings can be benefited.

Keywords: Accurate estimation; Estimating soil moisture content; IoT methods; Measuring soil moisture; Sensor methods.

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1. Introduction

According to soil-forming factors, the soil is essentially an unconsolidated material layer that is present at the surface of the earth [60]. Spaces or voids that exist between soil particles are called pore spaces. Both water and air can be contained in these voids [15]. Under normal circumstances, water will tend to drain away from the soil because the earth's gravity prevents it from holding all of the water in its pores [51]. Water held inside the soil is known as soil moisture. Precipitation, temperature, soil properties, and other factors all have an impact on it [5]. The water in the top 10cm of the soil is known as surface soil moisture. The water that is available to plats that are considered to as the upper crest of the ground, say with 200 cm of soil, is known as root zone soil moisture [22]. The entire quantity of water, such as water vapor, in unsaturated soil, is known as soil moisture. The word "soil moisture" indicates soil water that is found in soil pores rather than in rivers, lakes, or groundwater on land surfaces [16]. Soil moisture also describes the initial boundary condition of the terrestrial hydrological procedures, such as runoff, evapotranspiration, and infiltration [24].

The assessment of soil moisture content is vital for comprehending the hydrologic cycle and its consequences on climate, plant development, groundwater storage, etc. Soil moisture is among the most influential influences on soil nutrients. Fertilizers in general will yield a higher economic return when soil moisture levels are exceeded [47]. The soil's moisture content is a reliable indicator of the severe requirement for irrigation. Therefore, it serves as a crucial indication of the management of irrigation water [46]. Soil moisture is very dynamic both spatially as well as temporally [53] which makes it challenging to gather accurate measurements [6, 45]. As the population is increasing, the demand for potable water is also increasing putting constraints on irrigation water needs. Therefore, there is a need to optimize the utilization of irrigation water management and its efficacy. Therefore, for the optimal distribution of water, a precise and accurate measurement of the soil moisture content is needed [46]. Soil moisture content estimation is possible through various methods such as "combining satellite-derived values of vegetation index and IR skin temperature [19], assimilation of satellite-derived infrared (IR) heating rates to a numerical model [29, 30, 39, 72], direct usage of passive microwave remotely sensed data [68], Microwave Radar methods [2], Soil Moisture Active Passive Satellite [64], as cited in passing to [27].

However, it has been noted that the enormous footprint (from 25 km at 37 GHz to 150 km at 6.6 GHz) of the low-resolution, passive microwave data makes them less valuable for cloud- and mesoscale applications. In situations with substantial plant cover, data from such satellites are not becoming optimally effective for determining the moisture of soil [44]. Therefore sensor-based soil measurement can be conducted in passing to [36].

2. Method

Accurate assessment of the soil moisture is vital for successfully improving the crop yield efficiently using agricultural resources and effectively managing the water resources. The current paper aims to represent different methods of estimating soil moisture being adopted for civil engineering and agricultural engineering domain perspectives such as microwave, radar, and sensor-based methods from the electronics and communication engineering field and also artificial intelligence-based from computer science and engineering field termed as the state of the technology-based methods.

2.1 The Hydrologic Cycle as the Principle

The dynamics of estimation of soil moisture and its presence are based on hydrological balance where the balance equation is: Water inflows = Water outflows. Water inflows and outflows represent the variation in the amount of water stored in some areas over time [23]. Water inflows consider aspects of water related to capillary rise, rainfall, and irrigation. Water outflows consider aspects of deep percolation, runoff, transpiration, and evaporation [9]. Thus the following equation presents the soil moisture Θ and can be used to measure the field water storage as follows [36], the overall formula can be seen in equation 1.

$$\Theta(t) = ir(t) + rf(t) + cr(t) - etc(t) - dp(t) - ro(t) \quad (1)$$

Where moisture of the soil changes in the root zone $\Theta(t)$ based on water outflow because of run-off $ro(t)$, deep percolation $dp(t)$, rainfall $rf(t)$, crop evapotranspiration, $etc(t)$, capillary rise $cr(t)$, and effective irrigation $ir(t)$.

2.2 Determination of Soil Moisture Methodology

Soil moisture determination is among the most difficult parts of measurement in hydrology. Soil moisture measurement methods range from using the method of feeling and appearance of soil to using complicated electronic equipment using radioactive substances [28] and further using emerging technologies such as sensors as a part of remote sensing techniques [51]; measuring soil moisture with sensors using CRASP methodology [8]; measuring on Cloud IoT and Android systems (Vani & Rao, 2016) [65]; Artificial Intelligence (AI) methods [27] & AI methods using remote sensing data [4, 41, 3]. The following 3 methods are usually used for determining soil moisture [51, 20, 37, 48]: (i) In-situ methods or point measurement methods (ii) Remote sensing methods (iii) Soil-water models, and (iv) Prototyping IoT-based sensing and actuating with microcontrollers (v) Predictive techniques. In all these methods, there are some direct techniques such as Gravimetric, nuclear, and electromagnetic techniques, and indirect measurement techniques such as Capacitive, resistive, tensiometry, and hygrometric techniques [65] that are applied to measure the content of soil moisture.

2.3 Prototyping Methodology

Prototyping Methodology: In this research, prototyping IoT-based sensing and actuating with micro-controller-based methodology has been adopted. Prototyping is one of the design methodologies that decreases errors as well as removes the factors related to failures during the initial design phase [63]. Prototyping is a process that includes the test-refinement-competition of designs by utilizing the prototypes. Prototypes have been utilized to test if the design is responding to the intended functional and non-functional performances. Performance can be understood as quality criteria for key performance indicators (KPIs). Prototype helps reduce the risk involved and product development and testing as cited in Passing to [32]. Prototypes can be compared to laboratory experiments in terms of observations in terms of the impacts of design decisions and their real-world use. This approach extends beyond designing for practical application and emphasizes design thinking for assessment. For instance, prototypes can utilize an embedded model where users engage directly with devices integrated into the surroundings [62].

2.4 The CRASP methodology

The CRASP methodology: CRASP is a conceptual management methodology at the phenomenon level proposed initially by Dr. Mohammed AlSudairi & Dr. T. G. Vasista during the year 2014 at King Saud University Riyadh, KSA and subsequently put efforts towards its adaptability to drive the manifestation of IoT-based prototyping. Functional features of IoT-based prototyping show the feasibility of its implementation for construction safety management earlier [68] and now attempting the automated irrigation system feasibility. CRASP methodology aims to increase efficiency including teamwork, data analysis, stakeholder involvement, and project management solutions across IoT networks [68]. Prototyping provides the establishment of adapting changes aligning to customer requirements and outcomes [11]. From the Software Project Technology Management Control perspective, it adopts what is called the control process feedback loop figure-3 [67] and follows Rapid Prototyping Design Thinking (RPDT) methodology, which is nothing but embedding rapid prototyping of software engineering life cycle models within the design thinking model as cited in [67]. It manifests the feasibility of realizing the IoT-based implementation of features of smart irrigation systems [68]. Though it does not match the Product-Market Fit, which is important for entrepreneurship startups, however, it projects the problem-solution-fit as mentioned in [11] while following Bening's Rapid Prototyping based Design Thinking Methodology as cited in [67].

2.5 The Methods or Techniques of Estimating Soil-moisture

As mentioned in Somnath's article [58], there are different forms of methods: **(1)** Direct Measurement Techniques: Direct measuring techniques [57] include the elimination of water from soil samples using evaporation and chemical reactions. As in equation 2.

Moisture content (%) = (wet soil weight– dry soil weight)/ dry soil weight *100. (2)

Methods related to direct measurement are: Feel and Appearance Method: Gravimetric or Thermo Gravimetric method and Nuclear methods. (2). Indirect Measurement Techniques: Measurement of some properties of soil that are impacted by soil falls under indirect measurement techniques. These techniques measure the volumetric soil moisture content more quickly and accurately [42] than those from direct measurement techniques. Volumetric water content (%) could be computed if the soil's bulk density is known. As in equation 3 and Depth of water per unit soil depth in equation 4.

Volumetric "water content (%) = (wet soil weight– dry soil weight)/ dry soil weight*100* BD. (3)

Depth of water" per unit soil depth = Volumetric water content*soil depth (4)

Such as Tensiometric, Hygrometric, Capacitive, and Resistive fall under indirect measurement techniques. (3). Remote Sensing Techniques: It includes the direct usage of passive microwave remotely sensed data, active passive satellite-based soil moisture data, IR heating rates into numerical models, and a combination of satellite-derived values of vegetation index and infrared skin temperature [30]. The measurement of electromagnetic radiation, which is either emitted or reflected from the soil surface, is required for soil moisture's remote sensing. However, the most common method applied for estimating soil moisture is by using indirect approaches such as pressure membrane apparatus, pressure plate, neutron probe, and gypsum block as well as tension meter [17]. As the scope of this paper is limited to Sensor-based IoT methods, this section discusses only these methods in detail.

2.6 Materials & Sensor-based IoT Methods

The content of water inside the soil is determined via soil moisture sensors. These sensors can be of two types: (i) stationary – these are placed at predetermined locations in the fields or (ii) portable – these sensors measure soil moisture at several locations [74]. Soil moisture sensors can be installed in two ways: (i) by digging a hole and installing sensors at different depths or (ii) by using an auger to bore a hole and install vertically. Locations are flagged to easily access the sensor; sensors are monitored to note data readings every two to three days or a data logger can be used to store and log the data. This data is used for interpretation and quick decision-making purposes [54]. Moreover, Soil moisture sensors work under the principle of using the association between water content as well as electrical resistance to determine the moisture levels of soil [55]. For example, soil moisture can be measured for the evaporation loss of moisture over time. Optimum soil moisture content can be evaluated for various species of plants. It can be used to control irrigation in greenhouses [14].

2.7 Arduino with Analog pin output

Under Arduino setup, soil moisture can be measured by using 2 significant exposed pads, which function as probes for the sensor. Low resistance and higher SIG out indicate that the conductivity between the pads is stronger the more water there is in the soil or other material. Two pins GND and VCC are linked to Arduino to receive SIG out. A 4-pin jumper wire is connected to the sensor during wiring (See Figure 1). Arduino setup uses the following items: FTD Basic (3.3 V), USB cable, Soil Moisture sensor, Jumper wires and a breadboard, a smartphone, and a computer [14]. The internal comparator circuit's digital output is provided by the digital output pin. The Analog out pin provides an analog signal between the supplies to zero volts. An analog output pin on the Arduino is linked to one of its analog inputs.

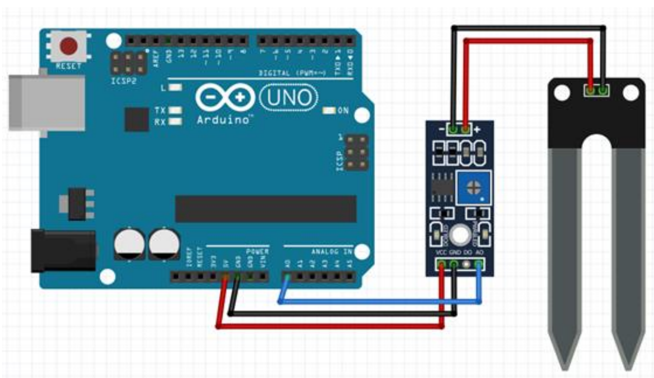


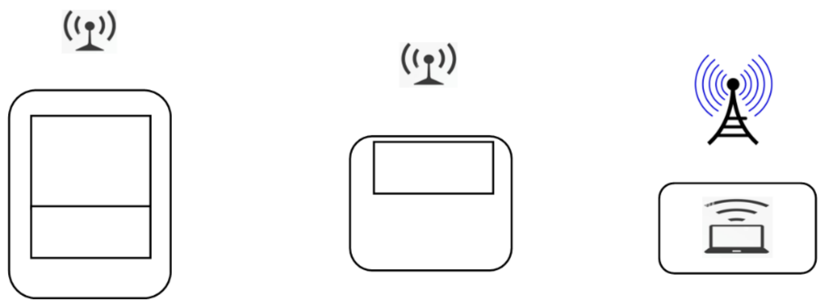
Figure 1. Soil-moisture sensor with Arduino board

2.8 Arduino with Digital Pin Output

The sensor is powered via the VCC pin. The recommended voltage range to power the sensor is 3.3V to 5V. A GND pin connects to the ground. Based on Arduino programming, the analog test reading values may be displayed as follows: ~850 for the Soil at Dry status and ~400 for the soil at completely wet status. For digital pin testing, the values show as follows: <500 are too wet; the target range is 500-750, and >750 indicates the dry state (means to be watered), correspondingly the LED can be made glow when the status of the soil is wet and LED is OFF for dry soil (lastminuteengineers.com). The soil dielectric permittivity is determined by the soil moisture sensor, which uses a capacitor to examine the soil's water content. M393 Integrated Chip (IC) does the voltage comparison with a reference voltage that is set by the adjustable potentiometer. LM393 comparator gives the digital value output indicating that the sensor has triggered the threshold value [61].

2.9 Measuring and Monitoring Soil Moisture Sensors in Wireless Sensor Network Environment

WSNs (Wireless Sensor Networks) are self-configured interconnected sensor nodes that communicate with each other to gather data about the surrounding setting and monitor physical and environmental conditions for further analysis and interpretation [38]. Every sensor node is equipped with at least one or more than one sensor, a processor, a power supply, and a radio transceiver section [10].



(a) (b) (c)

Figure 2. (a) Sensor Node, (b) Relay Node, and (c) Base Node Connected to PC Workstation

2.10 Functional activities of Various Nodes and their Brief Description

a) Sensor Node: Data collection, storage of sensor data, identification, and Radio communication [33].
b) Relay Node: Storage, identification, and Radio communication (For long-range transmission) [34].
c) Base Node: Identification, Radio communication, and USB communication (Wikipedia: WSN)
d) The base node transmits the whole data to pc workstation through a USB connection to analyze interpret and display results as mentioned by [71] in passing.

Sensor nodes are placed below the ground. They are used to collect soil measurements through well-integrated sensors. The sensor node transmits these measurements to a nearby relay node which is located above the ground. The relay node is responsible for forwarding data to other relay nodes or the base node.

3. Result and Discussion

3.1 Experiment 1: Automatic Regulation of Water based on the state of soil moisture (Dry state or Wet state).

An automatic water-controlling system based on soil moisture utilizes a soil moisture sensor to evaluate the amount of moisture that is present in the soil and control the irrigation system valves [35]. An experimental study is conducted on black cotton clayey soil using a Soil moisture sensor on the Arduino Uno board. The sensor detects the presence of water and sends a signal to stop the flow. It has the capability of achieving application efficiency above 90% basin irrigation by selecting the appropriate irrigation duration. The sensors are installed in the root zone of undisturbed soil and connected to the irrigation system controller; the controller then overrides schedule irrigation when plants don't need water anymore. In the Arduino Uno prototype, the sensor detects lower levels of moisture in the soil and activates the water pump to supply water to the plant. When a plant's soil moisture gets sufficient water i.e. when the soil gets wet, the sensor senses sufficient moisture availability in the soil, correspondingly pump is going to get stopped automatically [21].

Thus it helps homeowners and businesses in reducing water wastage and promotes plant health. The microcontroller system is customized in a way that automation of the irrigation system controls the water flow regulation to the paddy field and also reduces the time to be spent by workers controlling the water level as cited in passing to [49]. For example, an automated irrigation system with a soil moisture sensor can save an average home 15000+ gallons of water annually.

After the irrigation system program is uploaded on the Arduino Uno board, the pump will get started and stop "depending on the moisture ratio limits set in the program. The percentage ratio limit of soil moisture permits the DC pump to irrigate with the water or stop the DC pump" [21].

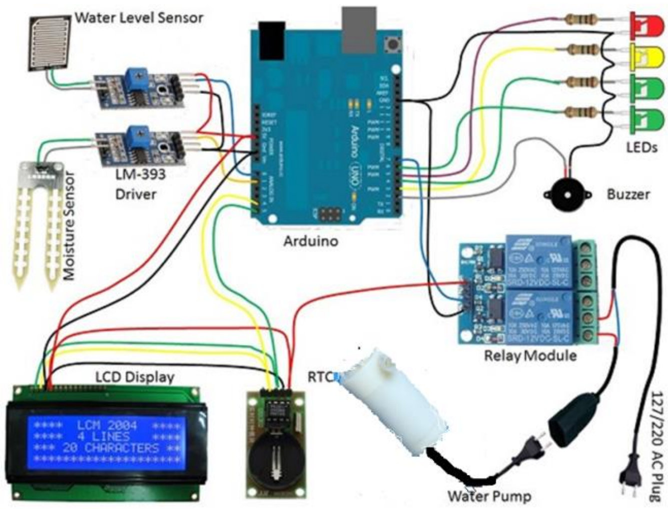
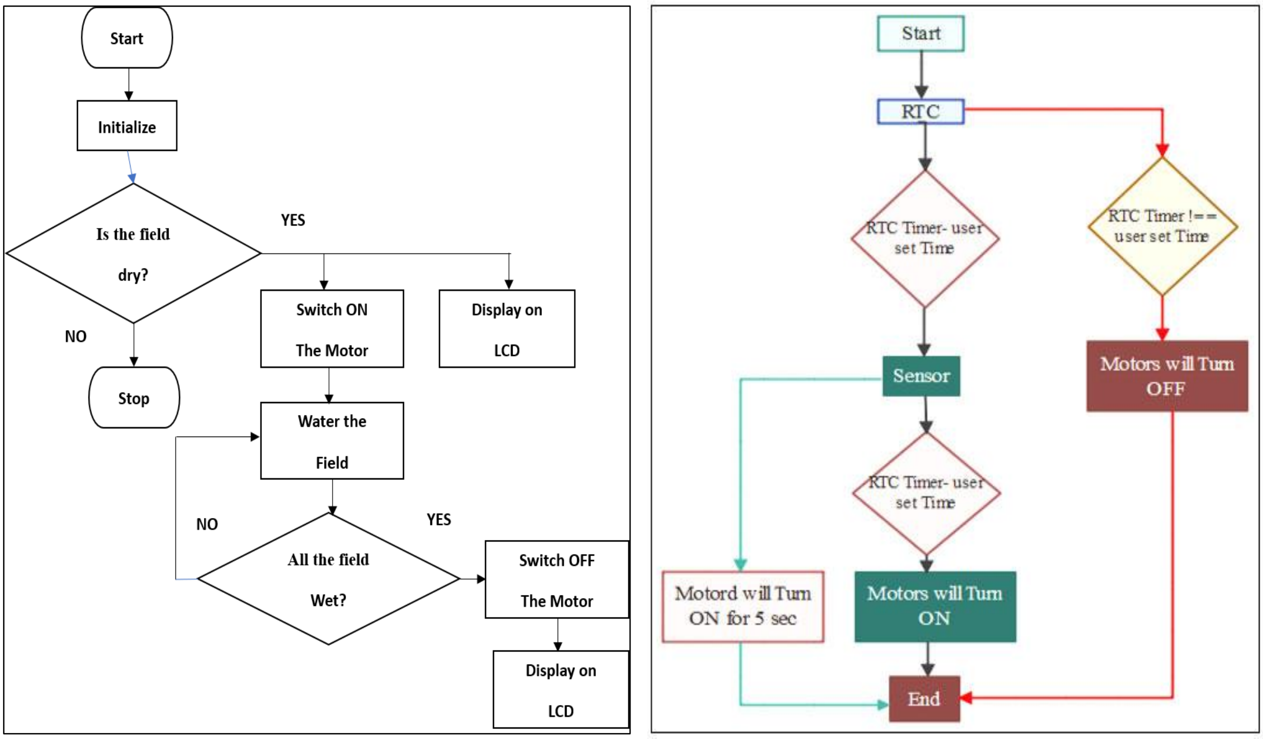


Figure 3. Proposed Automatic Water System Prototype using Soil Moisture Sensor, Water Level Sensor, and RTC DS3231 (*Source:* Embedded Labs - Modified)



(a) (b)

Figure 4. Flow Chart (Redrawn), (a) sources 50, (b), source 1

A timer module DS3231 is used. It is an I2C real-time clock (RTC), which maintains accurate timekeeping when the main power to the device I is interrupted. The DS3231 is available for commercial temperature range. The module includes an integrated potentiometer for adjusting the sensitivity of the digital output [43]. When the moisture level exceeds the threshold value set using a potentiometer, the module will output LOW otherwise MID or HIGH as per the range considered between 0-20 as LOW; 21-80 as MID, and above 80 as HIGH. In the timer module, the water supply time is set from 14:20 (2:20 pm) to 14:22 (2:22 pm), so that the motor pump becomes ON during that period and the motor pump becomes OFF after two minutes.

Figure 5. Pictures Taken During the Experiments (with Submersible Pump)

Furthermore, in a cinch, initially, as the plant is completely dry, the sensor detects low moisture value; and next, since the plant was already watered and became wet i.e. the moisture content is detected as 80% by the sensor, the motor pump becomes off. From the Proteus modeling software guidance, when the moisture of soil ratios became 20 percent & 40 percent (<50) the DC pump ran. At 80% DC pump had stopped [21]. The correlation between sensor output voltage and the percentage ratio of soil moisture is depicted by a linear variation curve, as illustrated in the tabular format and graph or Figure 6[66], Details can be seen in Table 1 and Figure 6.

Table 1. Sensor Voltage and Corresponding Soil Moisture Content

Sensor Voltage (V)	**0.41**	**0.82**	**1.23**	**1.64**	**2.05**	**2.46**	**2.87**	**3.28**	**3.69**	**4.10**
Soil Moisture (%)	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**

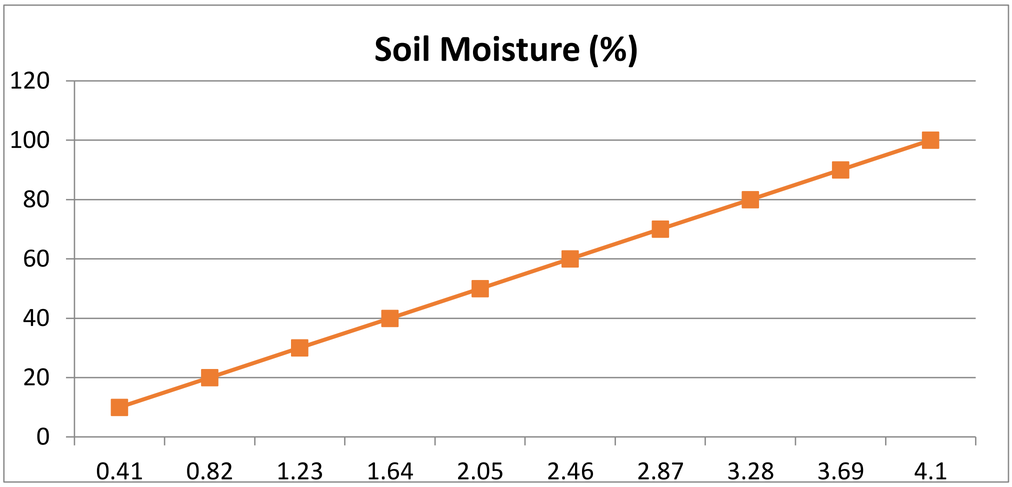


Figure 6. Graph showing the linear relationship between Voltage (on the X-axis) and Percentage Soil Moisture (on the Y-axis)

3.2 Experiment 2: Measuring the soil moisture percent of paddy soil through Soil Moisture Sensor

Soil moisture is important in monitoring agricultural lands (Sholihah et al., 2022) [56]. Traditional methods are time-consuming and do not offer real-time monitoring of the soil moisture. Soil moisture sensors are crucial for monitoring the levels of soil moisture in real-time. The sensors are capable of monitoring soil moisture levels in various locations within automated irrigation systems, as stated by Sharma (2019) [54]. Although these sensors provide more accuracy than traditional methods like the percolation method, sensor problems may arise due to corrosion especially when coming in contact with the saline content, and also reduce the accuracy of desired results (Songara & Patel, 2022) [59]. An experiment using a Soil moisture sensor on an Arduino Uno board has been conducted to calculate the soil moisture percentage present in the paddy soil. It has detected 80% of the black clayey (black soil but not very sticky) soil.

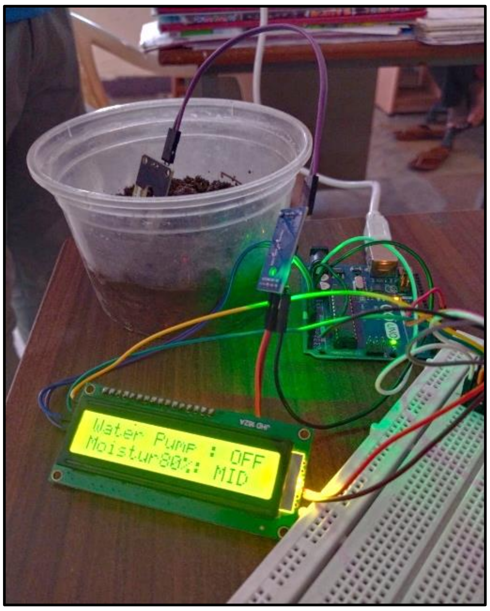


Figure 7. Soil Moisture Percentage Measured by Soil Moisture Sensor

3.3 Experiment-3: Percolation Method of measuring soil water holding capacity

Percolation is an important component of the hydrologic process, where water moves towards the ground. Deep percolation reduces water use efficiency as part of losses of water from the rice root zone in paddy fields, it accounts in the range of 50-80% of water input [12] as cited in [73]. Soil water holding capacity refers to the water volume that remains in the capillary gaps of the soil once gravitational water penetrates deeper soil layers [26]. The water holding capacity varies in several types of solids. While Sandy soils have poor water-holding capacity, black clayey cotton soils have a better capacity for water-holding [13].

Figure 8. Weighing Soil

Table 2. Water holding capacity of three soil samples (considered)

Sl. No.	Sample	Wt. of Sample (w) in g	Vol. of water Poured through w; v1 in ml	Vol. of water Collected in glass cylinder v2 in ml	Vol. of water retained in Soil (v1-v2) in ml	% of water holding capacity of soil
1.	Black Clayey Soil	25g	50ml	31 ml	19 ml	76%
2.	Road Side Soil	25g	50ml	36ml	14ml	56%
3.	Red Soil	25g	50	37ml	13ml	52%

When comparing the calculation of the water holding capacity method of soil by water percolation approach against the soil moisture sensor method, it has been observed a difference of 4% water holding capacity of the black clayey soil. By using soil sensor moisture, 80% is being displayed observed. Assuming that the sensor value is more accurate, the water requirement of paddy becomes more and safer for the farmer to request the government to get water supply towards yielding the paddy crop.

4. Conclusions

Monitoring soil moisture using soil moisture sensors will benefit environmental researchers, farmers, golf course-related staff, archeologists, and regulators. It helps to protect water resources and ever-changing climatic conditions. Soil moisture sensors are capable of measuring soil moisture at the root zone and regulating irrigation watering with considerable water savings with proper installation. This helps reduce water bills, fertilizers, pesticides, and other inputs. However, government incentives and subsidies can assist marginal farmers in coming forward to adopt these advanced soil monitoring techniques. According to [18] of the Soil Moisture Sensor market website, Soil moisture sensors are in nearly 3% of the global IoT sensor market. The soil moisture sensor market value of US$ 775.0 Million by 2033 with expected growth at a CAGR of 11.8% from 2023 to 2033 indicates the potential usage of soil moisture.

5. Suggestion or Future Research

Knowledge is central to the management of technology and managerial cognition [7]. It is important to include explicit knowledge in data-intensive and monitoring studies so that it brings new thoughts and approaches to the remote sensing field [40]. Therefore, using the dataset that is available on the ‘Kaggle’ website, watering the plants can be predicted by working on different supervised learning algorithms and comparing them to see which algorithms provide the best fit and accuracy for the data set. The best model (having high accuracy) predicts the target variable i.e. watering.

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