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IoT-Based Real-Time Soil Health Monitoring System for Precision Agriculture

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Abstract - *Monitoring soil health is a tedious and time-consuming task that requires intensive laboratory testing. Soil testing is a multi-step process that involves sample collection, proper packaging, and sending the soil to the nearest laboratory. The entire process requires a significant amount of time and resources and hence, it is not feasible to get real time soil health data from this approach. With the advancements in sensor technologies and data transmission protocols, it is now possible to monitor, collect, extract, analyze, and store real-time in-situ soil health data. In this article, we propose an IoT-based real-time soil health monitoring system using ESP32S3 that can measure soil moisture, electrical conductivity, pH, ultraviolet radiation, temperature, nitrogen, phosphorus, and potassium content of the soil. The system can choose from three communication protocols, Wi-Fi (IEEE 802.11), Global System for Mobile Communications (GSM) and Long Range (Lo-Ra) mesh networking based on their suitability to ensure real-time data transmission from the sensor units to the centralized server. The server also hosts a user-friendly web application interface for real-time visualization of soil parameters. The system is aimed at helping farmers or other stakeholders to take data-driven informed decisions to enhance crop yields in any cropping system.*

***Key Words*: soil-sensors, IoT-based, circuit, real-time, precision-agriculture, soil-health, ESP32, low-power**

1. INTRODUCTION

Soil is the most important natural resource and the foundation for life on Earth. Soil supports the entire agricultural systems in the world and the health of the soil dictates the availability of food for the global population. Soil is composed of minerals, organic matter, water, and air at different proportions. The weathering of the parent rock into fine particles due to its exposure to atmosphere and activity of different gases and water help in the formation of mineral base for the soil [1]. Additionally, microbial activity and plants and animals provide organic matter to the minerals, forming a soil suitable for plant growth and agricultural production [2]. Depending on the type of mineral or parent material involved in the formation of the soil and the amount of organic matter or nutrient available, the soil properties may vary across different regions and cause changes in yield [3]. The soil parameters including moisture content, light intensity, nutrients content, Cation Exchange Capacity (CEC), salinity, pH, and soil temperature directly influence the growth and development of crops. Hence, monitoring these variable soil parameters and implementing proper management strategies is vital for successful crop production.

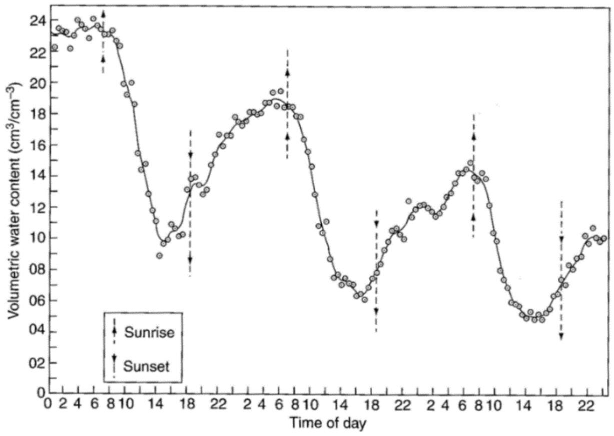

Chart -1: Soil moisture fluctuation in top 5 mm layer of loam soil on 5 to 7 days after irrigation [4]

The parameters such as soil moisture content, lux intensity and temperature can fluctuate significantly within a day because of several reasons such as rainfall, solar radiation, evapotranspiration, and soil drainage. Jackson (1973) measured the evaporation dynamics of soil surface in a loam soil in Arizona by measuring the volumetric water content of the top 5 mm of soil every 30 minutes. The diagram below shows fluctuations in soil moisture content of the top layer of the soil due to daily wetting and drying cycle [4].

The soil nutrient's availability also varies within a growing season due to factors including nutrient mineralization and immobilization, leaching, nutrient uptake by plants, and nutrient inputs and losses. The nutrient demand of the plants is also different at different growth stages [5]. The demand for nitrogen is higher in the plant's vegetative growth stages, whereas the demand for phosphorus and potassium increases during the reproductive stages [6]. Hence regular soil testing and monitoring is required for assessing the soil conditions and nutrient levels and implementing precision agricultural practices. However, the time and resource intensive soil sampling and testing procedure is a major challenge in the real-time soil health monitoring. Even though laboratory analysis is more accurate than using sensors, a tradeoff must be made for continuous soil health data [7].

Advances in technology, particularly in the domain of robotics, artificial intelligence, and machine learning, have made it possible to adopt precision agricultural practices by ensuring soil and crop health and eliminating inefficiencies [8]. Use of sensors and IoT technology can significantly help in real-time soil health monitoring by making it possible to collect real-time soil heath data continuously using sensors deployed in the field [9]. IoT platforms help in integrating the data collected by multiple sensors and send it to the centralized location or server for further analysis and the use of advanced analytics algorithms aid in providing valuable insights to the farmers [10]. The proposed system in this study helps in monitoring the real-time soil health parameters using sensors that can be strategically installed at different parts of the field. The sensor unit is designed to withstand harsh environmental conditions to ensure long-term field deployment. Multiple communication protocols can be used based on their feasibility for data transmission from sensor units to the centralized server. There are three primary communication protocols, Wi-Fi, GSM and Lo-Ra mesh networking that can be chosen based on the user requirements. The use of multiple modes of data collection ensures reliable data transmission in the varying geographical and infrastructure landscape. For the visualization and analysis of the real-time soil health data, a user-friendly web application interface has been hosted on the centralized server.

2. LITERATURE REVIEW

2.1 Soil Sensors

Soil sensors are vital tools for measuring various soil properties capable of influencing soil health and plant growth. There have been attempts to measure the soil parameters using different kinds of sensors either for map-based soil sensing or real-time sensing. Soil sensors can be broadly classified based on their working mechanisms or operating principles. Electrical or electromagnetic sensors are used to measure soil parameters based on the electrical conductivity or resistivity of the soil. Examples of this kind of sensor include capacitive soil sensors, resistive soil sensors, Electrical Conductivity (EC) sensors, Time Domain Reflectometry (TDR) sensors, and Frequency Domain Reflectometry (FDR) sensors. Similarly, optical sensors use optical characteristics of the soil for the measurement. They usually utilize Near-Infrared (NIR) spectroscopy and Visible (VIS) spectroscopy for measuring soil parameters [11]. In a similar manner, mechanical sensors such as penetrometer and tensiometer as well as electrochemical sensors such as conductometric and ion-selective electrodes can also be used to measure several soil parameters [12][13]. However, electromagnetic or electrical sensors and electrochemical sensors are the most widely adopted, low cost, and reliable sensors for soil health monitoring [14]. Electrical soil sensors typically use contact electrodes to measure the electrical properties of the soil and correlate them with the corresponding soil parameter being measured [15]. Multi-parameter soil sensors, that can measure multiple soil properties simultaneously, are also used for soil health monitoring [16]. Hence, appropriate soil sensors are used with suitable communication protocols for continuous and reliable soil health monitoring.

2.2 IoT for soil health monitoring

Internet of Things (IoT) is a network of interconnected objects embedded with sensors or sensor units or “things” that are capable of exchanging information within the network [17]. These objects can be household appliances, automobiles, and smart devices that have a unique address based on a standard communication protocol. IoT enables these objects to collect and transmit data autonomously, facilitating real-time monitoring, control, and optimization of processes across various domains including smart homes, healthcare, agriculture, and manufacturing [18]. IoT plays a vital role in making real-time soil health monitoring possible and has been adopted in several soil health monitoring systems. Bhatnagar et al. [19] proposed a soil health monitoring system using IoT that allows farmers in Jaipur, Rajasthan, to use an Android smartphone to monitor soil moisture, temperature, and pH, and receive lime and Sulphur recommendations based on pH levels. Similarly, another study by Ramson et al. [20] proposed an IoT-based soil health monitoring system using solar-powered units that transmit various soil health metrics wirelessly for continuous in-field monitoring, with data accessible through a web-based dashboard. Goswami et al. Also developed a portable, IoT enabled soil probe for real-time analysis of soil macronutrients (N, P, K), moisture, pH, and humidity, using LEDs and LDR for detection, with data accessible through a bilingual web interface, aimed at improving farmers' decision-making regarding crop selection, fertilization, and irrigation [21]. Sivakumar et al. also developed a system with integration of IoT and GIS for real-time soil health monitoring [22]. Similarly, Wu et al proposed a multi-sensor system based on IoT for monitoring soil health with real-time data transmission [23].

2.3 Message Queuing Telemetry Transport (MQTT)

MQTT is a lightweight messaging protocol designed for efficient communication between devices in constrained environments, such as IoT devices. MQTT operates at the application layer of the OSI (Open Systems Interconnection) model. Over the years, it has evolved into a widely adopted protocol that provides efficient data exchange in various IoT applications, including smart homes, industrial automation, healthcare, and agriculture [24]. It is a data-agnostic protocol that can transmit data in various formats such as binary data, text, XML, or JSON and uses a publish/subscribe model rather than a client-server model. MQTT uses a publish-subscribe messaging pattern, where clients (publishers) send messages to a central server known as the broker, which then distributes these messages to interested clients (subscribers) based on predefined topics [25].

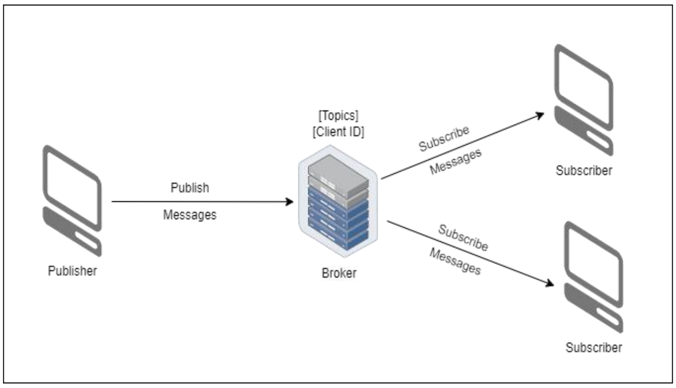

Fig-1: MQTT protocol

2.4 Wi-Fi (IEEE 802.11)

Wi-Fi (Wireless Fidelity) is a technology that allows electronic devices to connect to the internet and communicate wirelessly without the need for physical connection within a Local Area Network (LAN) [26]. The primary bands for operation of Wi-Fi are 2.4 GHz and 5 GHz frequency bands, and with recent advancements in the technology, a 6 GHz band (Wi-Fi 6E) has been introduced. Wi-Fi is governed by IEEE 802.11 family of standard and it has different versions such as 802.11a/b/g/n/ac/ax, each having some improvement in speed, range, and efficiency [27]. The ease of deployment and comparatively low cost makes Wi-Fi a preferred choice for both personal and enterprise networks. Wi-Fi has also proven to be a reliable mode of communication for several IoT systems.

2.5 Global System for Mobile Communications (GSM)

GSM is a standard developed to define the communication protocols for 2G digital cellular networks used by mobile phones. It was developed to create a single unified standard for mobile communications in Europe but soon became a global standard for mobile communication due to its effectiveness and efficiency. GSM system uses two bands of about 25 MHz each in the frequency range of 890 to 950 MHz for uplink (mobile to base station) and 935 to 960 MHz for downlink (base station to mobile) communication [28]. This usage of two separate bands of frequencies for uplink and downlink communication is also called Frequency Division Duplex (FDD), which ensures simultaneous two-way communication. GSM uses Frequency Division Multiple Access (FDMA) along with FDD. However, instead of having one channel per FDMA carrier, GSM arranges eight channels within a Time Division Multiple Access (TDMA) framework. This means that each 200 kHz FDMA channel is divided into eight time slots, allowing multiple users to share the same frequency channel by transmitting in their designated time slots [29]. GSM also introduced a system to use a Subscriber Identity Module (SIM) card that allowed users to switch mobile phones while retaining their phone number and identity [30]. GSM plays an important role in IoT by providing a power-efficient and reliable means of communication for different IoT devices. As GSM is available globally, it ensures coverage and availability in most of the urban as well as rural areas.

2.6 Lo-Ra and LoRaWAN

Lo-Ra is a wireless communication technology, derived from Chirp Spread Spectrum (CSS) technology, and designed specifically for long-range, low-power, low-data-rate communication. Due to its properties such as long range and low-power consumption, it is widely used in IoT systems [31]. It is a wireless modulation technique that can achieve long range communication with low interference and multipath fading. LoRaWAN is often used with Lo-Ra and is a Media Access Control (MAC) layer protocol built on top of Lo-Ra. LoRaWAN is a suitable communication protocol and network architecture for transmission of few bytes of sensor data over long communication distances. The LoRaWAN end devices are designed for transmitting signals over long distances and consuming low power. This makes this technology a popular choice for IoT systems [32].

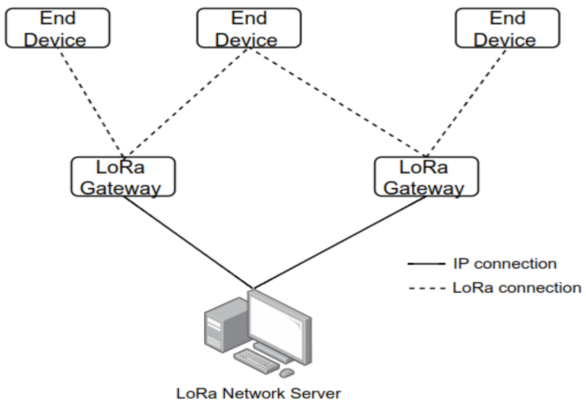

Fig-2: LoRaWAN Architecture

LoRaWAN-based IoT systems have been widely used in precision agriculture too. Silva et al. Used low power data acquisition devices in a vineyard at the UTAD University Campus to assess the effectiveness of LoRaWAN technology for systematizing data acquisition in precision agriculture using the mySense framework. The use of LoRaWAN solved the issues with range of data communication and energy budget [33]. Similarly, Soto et al. Also used LoRaWAN for communication in their soil health monitoring system to achieve low power data transmission from the sensor [34]. In another study, a soil moisture monitoring system using LoRaWAN was proposed that utilized Received Signal Strength Indicator (RSSI) and transmission power to indirectly sense the variations in soil moisture levels [35].

3. METHODOLOGY

3.1 Overall System Design

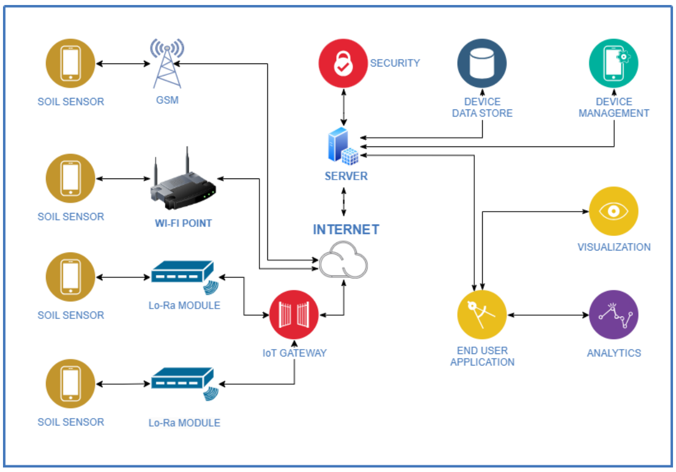

Fig-3: System Block Diagram

The overall system block diagram with general workflow of our system has been depicted in the above figure. The sensor units at different locations in the field can communicate with the centralized server using 3 different communication protocols, GSM for the cellular networking, Wi-Fi for the local area networking, and Lo-Ra for the long range, low power networking. In the case of LoRaWAN communication, data is collected and communicated through an IoT gateway that collects and forwards data to the other macro internet networking system that allows the data gathered to be sent to a base server. In the case of Wi-Fi communication, the inbuilt Wi-Fi functionality of the ESP32S3 helps to communicate directly to the central server. On the other hand, for a GSM system, it uses M2M communication to communicate with the server to send and store the sensor data. The central server takes care of data storage and sends the data to the connected mobile device for real-time data visualization and analysis.

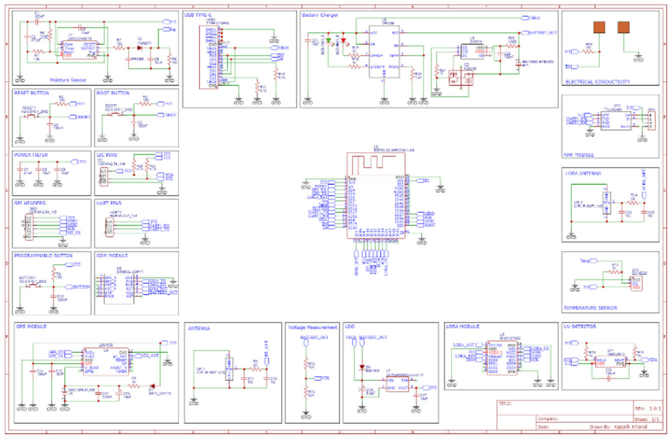

Fig -4: Circuit Diagram of the system

The circuit diagram has all the components of the proposed system with multiple communications and sensing interface. At the center of it is the ESP32S3 microcontroller with inbuilt Wi-Fi functionality. The power management in the system is handled through a USB Type-C connector, along with a battery charging circuit for portable use. The LDO regulator used in the system provides a stable voltage supply to all components with very low quiescent current of 9uA. To ensure reliability of the system, the circuit includes reset and boot with debounce circuits, a programmable user button, I2C, SPI, and UART expansion headers.

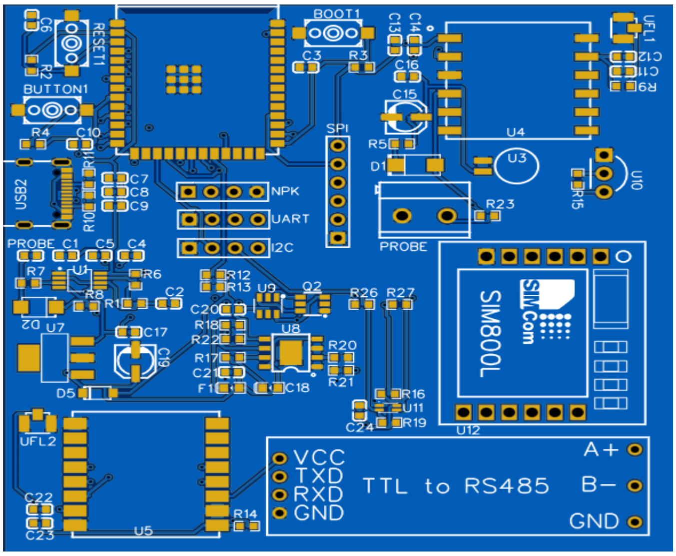

Fig-5: System PCB design

Special attention has been paid to maintain signal integrity and power supply cleanliness by placing the passive components such as the pull-up/pull-down resistors, bypass capacitors and filtering components properly in the circuit.

3.2 Sensor Functionality Overview

3.2.1 Capacitive Moisture Sensor

The core of the capacitive moisture sensor is a 555 timer that generates a square wave. The sensor operates based on the change in the soil's dielectric constant with the corresponding change in the soil's moisture content.

The frequency of the square wave generated by the 555 timer depends on R1, R6, C1, C2, and the PROBE capacitance. The oscillation frequency (f) of the 555 timer (in astable mode) is given by the following equation.

$$f = 1/\left(0.693 \cdot (R_1 + 2R_6) \cdot (C_1 + CPROBE)\right)$$

The ESP32 reads the capacitive moisture sensor's output by measuring the frequency of the output signal and counts signal pulses over a predefined interval, calculating frequency from this count. This frequency is then converted to a moisture level using pre-determined calibration data [36].

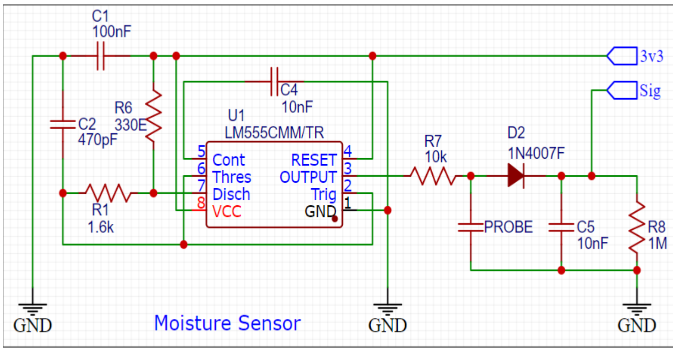

Fig -6: Capacitive moisture sensor circuit diagram

3.2.2 Electrical Conductivity Sensor

For measuring the electrical conductivity, two electrodes of copper plates, each 1 cm square in size, with 1 cm spacing between the plates were buried in the soil to create a voltage divider with a 1 mega ohm resistor.

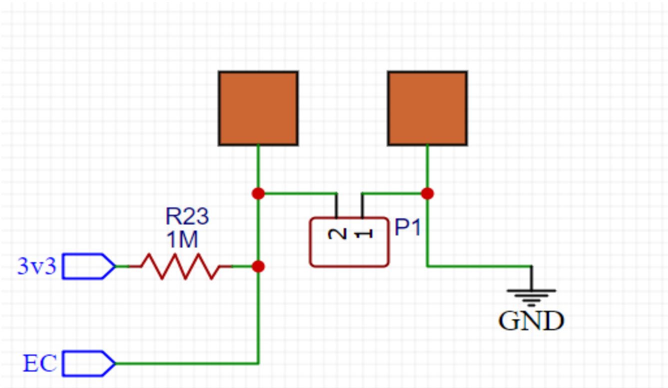

Fig-7: Electrical Conductivity sensor circuit.

When a 3.3V power source is applied, the soil's conductivity affects how the voltage is divided between the resistor and the soil. The relationship between this voltage and the soil's conductivity is inversely proportional to each other.

$$V_{out} = V_{in} \cdot \left(\frac{R_{soil}}{R_{soil} + R}\right)$$

Where, Vout is the voltage at EC pin, Vin is the 3.3V voltage supply, Rsoil is the resistance of soil, and R is a resistor with a fixed value.

$$R_{soil} = \frac{V_{out} \cdot R}{V_{in} - V_{out}}$$

Also,

$$Conductivity = \frac{L}{A \cdot R_{soil}}$$

Where, L is the distance between plates (1cm) and A is the area of plates ($1cm^2$). The above equation for conductivity becomes:

$$EC = \frac{(V_{in} - V_{out})}{V_{out} \cdot R}$$

This gives the conductivity in Siemens/cm.

3.2.1 Temperature Sensor

Similarly, the temperature sensor circuit used in this system uses a DS18B20 digital temperature sensor, and the sensor communicates using the 1-Wire protocol [37]. The DS18B20 provides direct digital temperature readings in Celsius, eliminating the need for analog-to-digital conversion. It uses its in-built 12-bit ADC that converts temperature data into binary format and stores it in a scratchpad memory along with configuration settings and CRC (Cyclic Redundancy Check) for error checking. The Dallas Temperature Library reads this data, checks the CRC value, and converts it to a raw value and the temperature in centigrade.

3.2.1 LUX Measurement Sensor

The UV detector circuit used in our system uses a VEML6075 component [38]. The VEML6075 is a digital UV light sensor that measures UVA and UVB radiation. It uses a photodiode array to detect light in the UV spectrum and converts this information into a digital signal that can be read by our ESP32 microcontroller.

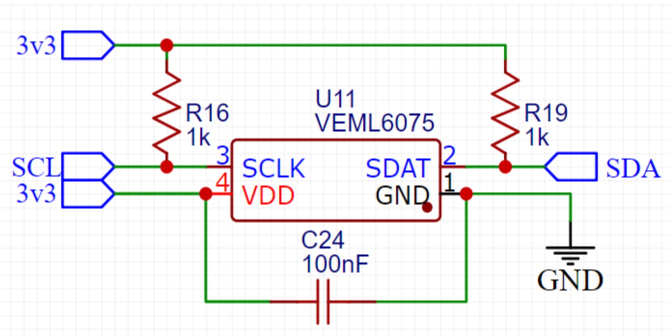

Fig-8: UV detector circuit diagram

The VEML6075 has separate photodiodes for UVA and UVB radiation which generates current when light falls onto it. The analog signals are then fed into an ADC, which converts them into digital values. These raw values must be converted using specific conversion coefficients. The UV index is a standardized measurement of the strength of ultraviolet radiation at a particular place and time.

3.2.1 NPK and pH Measurement

The NPK soil sensor module uses a combination of ion-selective electrodes (ISEs) and a calibration system to determine the concentration of these nutrients [39]. We used Taidacent RS485 sensor probe for the NPK and pH measurement. The NPK sensor uses ISEs specific to nitrate (NO3-), phosphate (H2PO4- or HPO42-), and potassium (K+). The sensor probes are inserted into the soil, and the electrodes measure the potential generated by nitrate, phosphate, and potassium ions. The sensor's internal microcontroller processes these potentials using the calibration data to calculate the concentrations of N, P, and K levels in the soil. The sensors communicate with the microcontroller using TTL to RS485 converter as sensor outputs in RS485 communication protocol and microcontroller do not accept that protocol. The sensor then sends back a response containing the measurement data.

4. RESULTS AND DISCUSSION

The real time soil data measured by the sensors is transferred using the appropriate communication protocol to the server. The central server stores the data in the storage and at the same time sends the data to the web application for visualization. The user interface of the web application displays real-time readings of each soil parameter. The visualization was highly interpretable and user-friendly and can be easily understood by anyone. The graphs below show the sensor data generated by our system. The numbers on the x-axis represent the time on twelve different splits or segments taken at an interval of 1 hour starting at 6 a.m., and the y-axis show the corresponding averaged values obtained from the soil sensor.

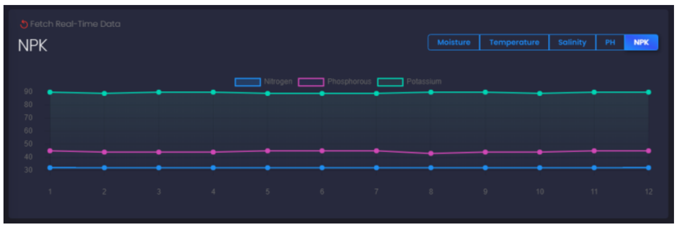

Fig-9: Visualization of Nitrogen, Phosphorus, and Potassium levels in the web application.

Fig-10: Visualization of moisture level in the soil in the web application.

Fig-11: Visualization of Soil Electrical Conductivity (Salinity) in the web application.

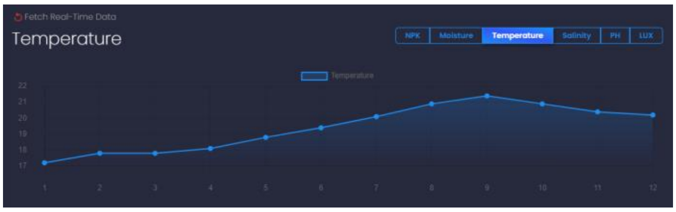

Fig-12: Visualization of Soil Temperature readings in the web application.

Fig-13: Visualization of Soil pH readings in the web application.

Fig-13: Visualization of LUX readings in the web application.

A comparative analysis was conducted to assess the accuracy and reliability of the proposed system. The data collected by our sensor was compared with the laboratory soil test results. A soil sample was collected from the same site where our system was installed to measure the soil data. We measured the Nitrogen, phosphorus, potassium concentrations and the electrical conductivity of the soil sample and compared the laboratory results with the data collected by our system.

Table -1: Soil parameter values comparison.

Parameter	Laboratory Analysis	Sensor Observations
pH Level	6.8	6
Composition		
Nitrogen (N)	83 mg/kg	89 mg/kg
Phosphorus (P)	51 mg/kg	45 mg/kg
Potassium (K)	34 mg/kg	32 mg/kg
Conductivity	189 us/cm	197 us/cm

We also computed the percent error to analyze how inaccurate the system measurement is, compared to the standard laboratory analysis of soil parameter.

Table -2: Percent Error for each parameter.

Parameter	Error Percentage
pH Level	11.76%
Composition	
Nitrogen (N)	7.23%
Phosphorus (P)	11.76%
Potassium (K)	5.88%
Conductivity	4.23%

It was observed that the soil test results closely match with the results from laboratory analysis of the soil sample. This gives a strong indication that the proposed system is accurately reflecting the soil conditions. However, the system's reliability in field conditions must be assessed for long-term use.

3. CONCLUSIONS

Our study shows the potential and practicality of utilizing an IoT-based system for real-time soil health monitoring. By using advanced sensors and communication protocols such as Wi-Fi, GSM, and Lo-Ra, the proposed system can measure soil parameters that include soil pH, electrical conductivity, moisture, ultraviolet radiation, temperature, and key nutrients such as nitrogen, phosphorus, and potassium. The user-friendly web application interface enables effective visualization and analysis of the soil health parameters instantaneously. This system can help take informed, data-driven decisions in agriculture that can significantly enhance crop yields and productivity. Our proposed system addresses the limitations of traditional soil testing methods, offering a more efficient, resource-effective, and timely solution for monitoring soil health.

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