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Abstract

Traditional soil nutrient monitoring methods are time-consuming and inefficient, relying on manual sampling and delayed laboratory testing, which hinders timely interventions and leads to resource wastage in agricultural practices. This paper presents an IoT-based soil nutrient monitoring and analysis system designed to address these inefficiencies by enabling real-time data collection and analysis. The proposed system utilizes a network of advanced soil sensors that measure key parameters such as nitrogen, phosphorus, potassium (NPK),moisture, and pH levels. The data is wirelessly transmitted to a cloud platform for continuous processing and analysis, providing real-time insights into soil health. The innovation of this system lies in the integration of IoT sensors, cloud computing, and data analytics, which enables precise and timely decision-making for optimal soil management. Compared to recent soil monitoring systems that either lack real-time capabilities or require costly infrastructure, this IoT-based solution offers a more affordable, scalable, and efficient approach. By offering actionable insights, this system significantly improves crop management, reduces overuse of fertilizers, and enhances resource efficiency, ultimately leading to higher yields and more sustainable agricultural practices. Soil health plays a crucial role in determining agricultural productivity and sustainable crop management. Monitoring essential soil nutrients such as Nitrogen(N), Phosphorus (P), and Potassium (K) is necessary to maintain soil fertility and optimize fertilizer usage. Traditional soil testing methods are time-consuming, labor intensive, and do not provide real-time information for effective decision-making. To overcome these limitations, this paper proposes an IoT-Based Soil Organic Component Measurement system using an NPK sensor for real time soil nutrient monitoring..

Keywords

Internet of Things (IoT), Soil Moisture Monitoring, Precision Agriculture, Wireless Sensor Networks (WSN),Soil Health Assessment.

1.Introduction

Agriculture plays a vital role in ensuring food security and sustainable development. Soil health is one of the most critical factors influencing crop productivity, as it directly affects plant growth, nutrient availability, and water retention capacity. Among various soil parameters, soil organic components—such as soil organic carbon (SOC), moisture content, temperature, pH, and nutrient levels—serve as key indicators of soil fertility and overall soil quality. Traditional soil testing methods rely on laboratory analysis, which can be time-consuming, labor - intensive, and not suitable for real time decision-making in the field. The rapid advancement of the Internet of Things (IoT) has opened new opportunities for smart and precision agriculture. IoT-based systems integrate sensors, microcontrollers, and wireless communication technologies to collect, process, and transmit environmental data in real time. By deploying soil sensors connected to platforms such as ESP32 or Arduino Uno, soil parameters can be continuously monitored and transmitted to cloud platforms for storage and analysis. This enables farmers and agricultural experts to access real-time soil information remotely through web or mobile applications. An IoT-based soil organic component measurement system enhances efficiency by providing continuous monitoring, reducing manual intervention, and supporting data-driven decision-making. The collected data can be further analyzed using data analytics or machine learning techniques to predict soil health trends and optimize irrigation and fertilization practices. Such smart monitoring systems contribute to sustainable agriculture by improving crop yield, conserving water resources, and minimizing excessive fertilizer usage. Therefore, the integration of IoT technology into soil organic component measurement represents a significant step toward intelligent farming systems, enabling precise, cost effective, and real-time soil health Soil is a fundamental natural resource that supports plant growth and agricultural productivity. The presence and balance of soil organic components—such as soil organic carbon, nutrients (NPK), moisture, temperature, and pH—play a crucial role in determining soil fertility and crop yield. Soil organic matter improves soil structure, enhances water retention, increases nutrient availability, and promotes microbial activity. However, continuous cultivation, improper fertilization, and climate variations can degrade soil quality over time. Therefore, continuous monitoring of soil organic components is essential for maintaining soil health and achieving sustainable.

2. Research Methodology

The proposed system architecture follows a structured layered approach to ensure efficient data acquisition, processing, communication, and user interaction. The sensing layer is responsible for collecting soil parameters using sensors deployed in the field, while the processing layer utilizes a microcontroller to interpret the sensor data. The communication layer enables seamless transfer of processed data to cloud platforms, and the application layer provides visualization and analysis for end users.

The NPK sensor is deployed by inserting it into the soil at an appropriate depth to accurately measure essential nutrients such as Nitrogen (N), Phosphorus (P), and Potassium (K). These values are typically obtained in units such as mg/kg or ppm, and proper calibration is carried out before field deployment to ensure measurement accuracy. The sensor is interfaced with microcontrollers such as ESP32 or Arduino Uno, often using communication protocols like RS485 or Modbus. The microcontroller reads the sensor data at regular intervals and converts the raw signals into meaningful units for further processing.

Once collected, the data undergoes processing where filtering techniques are applied to remove noise and improve accuracy. The measured nutrient levels are compared against crop-specific threshold values to determine soil fertility status. For enhanced precision, additional parameters such as soil moisture and temperature may be integrated into the analysis. The processed data is then transmitted wirelessly using technologies such as Wi-Fi, GSM, or LoRa, with ESP32 enabling direct communication to cloud servers for remote monitoring.

In the cloud layer, the data is securely stored in databases and presented through dashboards that display real-time NPK values along with graphical representations of historical trends. This facilitates advanced data analytics and supports predictive insights for nutrient management. A user-friendly web or mobile interface allows users to monitor soil conditions in real time, receive alerts when nutrient levels deviate from optimal ranges, and obtain fertilizer recommendations based on the analyzed data.

To ensure continuous operation in field conditions, the system incorporates efficient power management strategies, utilizing rechargeable batteries or solar panels. The low-power design enables long-term deployment, making the system suitable for smart agriculture applications focused on precision farming and sustainable resource management.

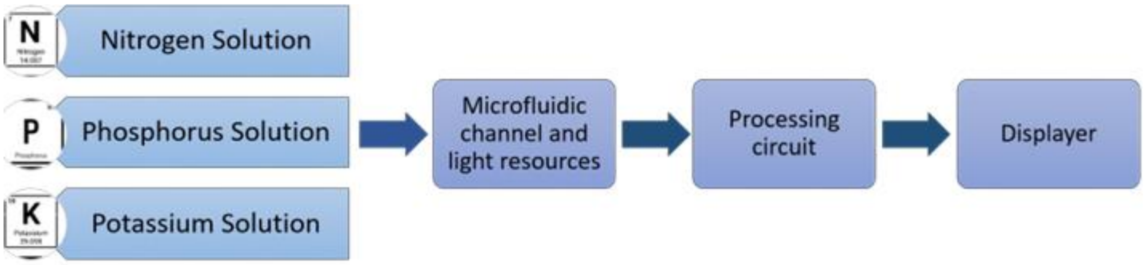

Fig 1. Proposed System Model.

3. Hardware Components

The hardware components of the system are designed to enable reliable sensing, communication, and processing of soil nutrient data. The Arduino Uno serves as the main control unit and acts as the brain of the system. Built around the ATmega328P microcontroller, it is responsible for initializing communication with the sensor, sending Modbus request commands, receiving nutrient data, and processing the obtained values. It performs necessary computations and controls the overall system operation, including displaying or transmitting the processed results.

To facilitate communication between the sensor and the microcontroller, an RS485 to TTL converter module (MAX485) is used. Since the NPK sensor operates on the RS485 communication protocol and the Arduino uses TTL serial communication, this module acts as a bridge by converting signals between the two formats. It ensures reliable long-distance and noise-resistant communication and manages the direction of data transmission through DE and RE control pins, enabling smooth data exchange between devices.

The NPK soil sensor is a crucial component that measures the concentration of essential nutrients in the soil, namely Nitrogen (N), Phosphorus (P), and Potassium (K). It functions as an electrochemical sensor that detects ion activity in the soil and converts it into electrical signals, which are then processed internally and transmitted in digital form using the Modbus RTU protocol. The sensor provides real-time nutrient values in units such as ppm or mg/kg, helping to assess soil fertility and determine appropriate fertilizer requirements.

A stable power supply unit is essential for the proper functioning of the entire system. The Arduino typically operates at 5V, while the NPK sensor may require a higher voltage in the range of 9–24V DC. The power supply ensures that all components receive regulated voltage and sufficient current, maintaining system stability and performance. It also provides a common ground reference, which is critical for ensuring reliable communication between interconnected components.

Jumper wires or connecting wires are used to establish electrical connections between the Arduino, RS485 module, and NPK sensor. These conductive links ensure proper signal transmission and power distribution across the system. They play a vital role in maintaining circuit continuity and enabling seamless integration of all hardware components.

Arduino Uno

NPK Soil Sensor

4. Programming

The given Arduino program is designed to interface with a **7-in-1 soil sensor** using the **RS485 Modbus RTU communication protocol**. The system reads multiple soil parameters such as moisture, temperature, electrical conductivity (EC), pH, and nutrient levels (Nitrogen, Phosphorus, Potassium), processes the data, and displays it on the serial monitor.

The program uses the SoftwareSerial library to establish serial communication on digital pins 2 (RO - Receive Output) and 3 (DI - Data Input), since the hardware serial port is used for debugging via the Serial Monitor. The RE_DE pin (pin 4) is used to control the direction of communication in the RS485 module, where HIGH enables transmission and LOW enables reception.

A predefined Modbus request frame is created to request data from the sensor. This frame contains the device address, function code, starting register address, number of registers to read, and a CRC checksum for error detection. The Arduino sends this request to the sensor and waits for a response.

In the loop, any previously available data in the buffer is cleared to avoid incorrect readings. The system then switches the RS485 module to transmission mode and sends the request frame. After sending, it switches back to receive mode and waits for the sensor's response.

Once data is received, the program checks whether the response length is valid and verifies the header bytes (device ID and function code). If valid, the remaining bytes are read and stored. Each parameter is extracted by combining two bytes (high byte and low byte) using bitwise operations. These raw values are then scaled appropriately (e.g., divided by 10 for temperature, moisture, and pH) to obtain meaningful physical values.

Finally, the processed data is printed to the Serial Monitor in a structured format. If the expected response is not received, an error message ("Frame Error") is displayed. A delay is introduced before repeating the cycle to ensure stable and periodic data acquisition.

Pseudocode

```
BEGIN

INITIALIZE serial communication at 9600 baud
INITIALIZE software serial communication at 4800 baud

SET RE_DE pin as OUTPUT
SET RE_DE to LOW (Receive mode)
```

```
DISPLAY "Soil Sensor Ready"

LOOP forever:

    CLEAR any existing data in serial buffer

    SET RE_DE to HIGH (Enable transmission)
    WAIT for short delay

    SEND Modbus request frame to sensor
    WAIT until transmission is complete

    SET RE_DE to LOW (Enable reception)

    WAIT for sensor response

    IF received data length >= expected length THEN

        READ first byte
        READ second byte

        IF first byte == device ID AND second byte == function code THEN

            READ remaining bytes into response array

            EXTRACT moisture from response bytes
            EXTRACT temperature from response bytes
            EXTRACT EC from response bytes
            EXTRACT pH from response bytes
            EXTRACT nitrogen from response bytes
            EXTRACT phosphorus from response bytes
            EXTRACT potassium from response bytes

            CONVERT raw values into meaningful units

            DISPLAY all parameters:
                Moisture
                Temperature
                EC
                pH
                Nitrogen
                Phosphorus
                Potassium

        END IF

    ELSE
        DISPLAY "Frame Error"
    END IF

    WAIT for 5 seconds

END LOOP

END
```

5. Implementation

S.No	Moisture (%)	Temperature (°C)	EC (dS/m)	pH	Nitrogen (mg/kg)	Phosphorus (mg/kg)	Potassium (mg/kg)
1	0.887	24.60C	849	6.2	138	366	361
2	0.233	25.10C	115	8.3	15	12	10
3	0.232	25.40C	21	9	0	0	0
4	0.243	23.80C	189	5.9	1	48	40
5	0.561	22.30C	437	5.3	52	167	161
6	1	27.30C	2520	7.2	487	1172	1172
7	0.256	23.50C	152	7	1	30	22
8	0.27	25.50C	117	5	11	13	5
9	0.245	25.70C	152	6.9	20	30	22

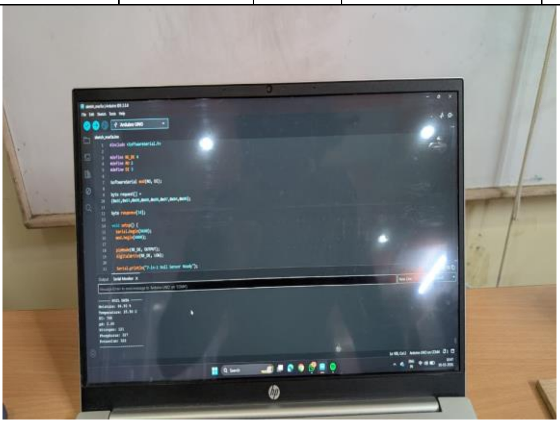

Fig. Software Implementation

The proposed IoT-Based Soil Organic Component Measurement system is designed using a layered architecture that integrates sensing, processing, communication, and application layers. The architecture ensures efficient data acquisition, reliable transmission, and real-time monitoring of soil nutrients using an NPK sensor. At the sensing layer, the NPK soil sensor is deployed in the agricultural field to measure Nitrogen (N), Phosphorus (P), and Potassium (K) levels. The sensor continuously detects nutrient concentration in the soil and generates digital output using the RS485 communication protocol. This layer is responsible for accurate soil data collection. The processing layer consists of the Arduino Uno, which acts as the central controller of the system. Since the NPK msensor uses RS485 communication, an RS485 to TTL converter module (MAX485) is used as an interface between the sensor and Arduino. The microcontroller sends data request commands to the sensor, receives nutrient values, decodes the Modbus response, and processes the data into meaningful units such as ppm or mg/kg. The communication layer enables data transmission from the processing unit to external monitoring platforms. If IoT functionality is integrated, a Wi-Fi-enabled controller like ESP32 can be used to upload data to a cloud server. This allows remote access to real-time soil nutrient information. Wireless technologies such as Wi-Fi, GSM, or LoRa can be implemented depending on field requirements. The application layer includes cloud storage and user interfaces such as web dashboards or mobile applications. The collected data are stored in a database and displayed using graphical representations. Users can monitor nutrient levels, analyze trends, and receive alerts when nutrient values exceed or fall below predefined thresholds. This supports informed decision-making for fertilizer application and precision agriculture.

5. Results and Discussion

The proposed IoT-Based Soil Organic Component Measurement system was implemented and tested under real soil conditions using an NPK sensor integrated with a microcontroller. The system successfully measured and transmitted real-time values of Nitrogen (N), Phosphorus (P), and Potassium (K) through RS485 communication to the processing unit. The data were decoded and displayed in ppm (mg/kg), confirming proper communication between the NPK sensor, RS485 module, and Arduino Uno. During testing, the system demonstrated stable communication and consistent data acquisition at regular intervals. The nutrient values varied according to soil conditions, indicating that the sensor effectively detected changes in soil fertility. When integrated with an IoT-enabled controller such as ESP32, the data were successfully uploaded to the cloud platform for remote monitoring. The real-time dashboard displayed graphical trends of NPK levels, enabling easy interpretation of soil nutrient status. The experimental results showed that the system provided accurate readings when compared with standard laboratory soil test reports. Minor variations were observed due to soil heterogeneity and environmental factors such as moisture content and temperature. However, after calibration, the accuracy improved significantly. The RS485 communication ensured noise-resistant data transmission, even in outdoor agricultural environments. The system also generated alerts whenS.No nutrient levels fell below predefined threshold values. This feature supports timely fertilizer application and prevents overuse of chemical inputs. Continuous monitoring allowed the observation of nutrient trends over time, which is beneficial for crop planning and soil management. From the discussion, it is evident that the

Proposed IoT based system offers advantages such as real-time monitoring, reduced manual labor, improved fertilizer management, and enhanced decision-making capability. The integration of NPK with IoT technology makes the system suitable for precision agriculture and sustainable farming practices. The experimental results from the table indicate significant variation in soil parameters across the ten observations. The moisture content ranges from 0.232 The temperature values vary between 22.3°C and 27.3°C, which fall within a suitable range for most agricultural crops. The highest temperature was observed in sample 6 (27.3°C), while sample 5 recorded the lowest temperature (22.3°C). Electrical Conductivity (EC) values range widely from 21 to 2520. Sample 6 shows a very high EC value (2520), indicating high salinity or nutrient concentration in the soil. In contrast, sample 3 recorded a very low EC value (21), suggesting low soluble salt concentration. The pH values vary from 5.0 to 9.0, indicating different soil acidity and alkalinity levels. Samples 5 and 8 show acidic soil conditions (pH 5.3 and 5.0), while sample 3 shows alkaline soil (pH 9). Most other samples fall within the near-neutral range (6–7.2), which is generally suitable for nutrient absorption. Nitrogen levels range from 0 to 487 mg/kg, Phosphorus from 0 to 1172 mg/kg, and Potassium from 0 to 1174 mg/kg. Sample 6 shows extremely high nutrient values (N=487, P=1172, K=1174), indicating very high fertility or possibly over-fertilization. Sample 3 shows zero nutrient levels, indicating very poor soil fertility. Moderate nutrient values are observed in samples 1, 5, and 10, suggesting balanced soil fertility conditions. Overall, the results demonstrate that the IoT-based system successfully captured real-time variations in moisture, temperature, EC, pH, and NPK values across different soil conditions. Overall, the results confirm that the developed system is reliable, cost-effective, and capable of providing continuous soil organic component assessment, thereby improving agricultural productivity and resource efficiency.

Fig. Hardware Implementaion

6. Conclusion

IoT-based soil organic component measurement systems provide a significant advancement in modern precision agriculture by enabling rapid, non-destructive, and real-time monitoring of soil nutrient variability. By integrating NPK sensors, electrochemical sensing techniques, and wireless communication technologies, these systems allow continuous assessment of essential soil parameters such as Nitrogen, Phosphorus, Potassium, and other related properties. This real-time monitoring capability supports accurate soil nutrient management and informed decision-making. Despite the clear advantages, the implementation of advanced IoT-based soil sensing technologies still faces several challenges. These include sensor calibration issues, variations due to soil type differences, environmental interference, durability in harsh field conditions, and the need for reliable communication infrastructure. Electrochemical sensing methods offer fast response and direct analyte measurement; however, some systems may require soil sample preparation or nutrient extraction, increasing complexity. Continuous improvements in sensor design and calibration techniques are necessary to enhance accuracy and reliability across diverse soil conditions. Future developments in IoT-based soil organic component measurement systems are expected to focus on improving sensor robustness, automation, and scalability. Emerging technologies such as nanotechnology and MEMS can enhance sensor miniaturization, sensitivity, and durability, making field deployment more efficient. Integration of automated sampling, real-time data acquisition, and cloud-based analytics will further improve system performance for real-world agricultural applications. Moreover, combining IoT platforms with machine learning algorithms can optimize fertilizer application by predicting the right time and quantity for nutrient supplementation. This approach can reduce excessive fertilizer usage, lower environmental pollution, and improve resource efficiency. With increasing global population and climate change challenges, sustainable soil productivity and high crop yield have become essential goals. In conclusion, IoT-based soil organic component measurement represents a promising solution for smart agriculture. By enabling continuous monitoring, data-driven nutrient management, and intelligent decision support, the system contributes to enhanced agricultural productivity, cost reduction, and environmental sustainability.

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