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IoT Based Soil Health Monitoring System

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ABSTRACT
The proposed IoT-enabled soil health monitoring system is an intelligent solution, providing real-time analysis of soil state and sustainability in agriculture. Conventional soil testing techniques are frequently time-consuming, laborious work, and cannot reflect the dynamic fluctuation of soil properties. Using Internet of Things (IoT) and incorporating sensors, wireless communication and data analytics, the system constantly tracks in real-time important soil parameters like pH, moisture content, temperature and nutrients (N,P,K levels). The data collected are uploaded to a cloud service for further analysis, allowing farmers to base irrigation, fertilization and crop management decisions on data. These systems not only save resources and increase the yield of crops, but are also effective measures for soil conservation as well as environmental protection. Artificial intelligence is also combined with predictive analysis to enable the early identification of soil degradation in order to take corrective action on time. In short, the system is a scalable and affordable tech that helps to drive precision farming in order to achieve sustainable food production.

Keywords: *Soil health monitoring, IoT application, Real time analysis, Precision farming.*

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I. INTRODUCTION

Soil health is essential for sustainable agriculture because it promotes plant growth, controls the quality of the air and water, and preserves ecosystem balance. Although accurate traditional soil testing techniques have limitations because they need laboratory analysis, take a lot of time and are unable to record changes in soil conditions in real time. Modern soil health monitoring systems overcome these limitations by combining wireless communication, artificial intelligence, and IoT-based sensors. Contemporary soil health monitoring systems get around these restrictions. Precision farming techniques like effective irrigation and nutrient management are made possible by these technologies, which enable Continuous monitoring of soil parameters like pH, moisture, organic matter, and nutrient levels. Additionally, these systems are scalable and resilient, operating well in harsh weather and for extended periods of time, without requiring regular maintenance. As a result, soil health monitoring has developed into a continuous, technologically advanced procedure that guarantees environmental sustainability and long-term soil productivity. The system assists farmers in making well-informed decisions that increase crop yield and minimize resource waste by supplying real-time data.

Several researchers have contributed significantly to the development of soil health monitoring systems by integrating sensing technologies, automation, and IoT frameworks. Marie [1] introduced an optical transducer-based system for detecting essential soil macronutrients such as Nitrogen (N), Phosphorus (P), and Potassium (K), enabling accurate nutrient quantification. Singh and Shaligram [2] designed an automatic soil fertilizer dispensing robot that measures NPK levels, showcasing the potential of automated nutrient management. Ramane [3] employed fiber optic sensors for nutrient detection, providing a reliable and low- cost solution for continuous soil analysis. Futagawa [4] developed a compact multimodal sensor capable of measuring soil pH, electrical conductivity, and temperature simultaneously, supporting precision agriculture applications. Bhatnagar and Chandra [5] proposed an IoT-based soil health monitoring and recommendation system, integrating real-time data transmission with smart agricultural decision-making.

Ahlmer [6] focused on soil moisture remote sensing to identify flood-prone areas, illustrating the broader environmental applications of soil data. Sobhy and Anandhi [7] presented a systematic review of soil nutrient monitoring technologies for sustainable agriculture, emphasizing the importance of technological integration and precision. Todd [8] analyzed sensor variability in low-cost soil moisture and temperature sensors, highlighting the need for sensor calibration and accuracy in agricultural use. Babaeian [9] explored ground- based and satellite remote sensing for soil moisture monitoring, bridging field- scale and regional-scale observations. Finally, Burton [10] introduced real-time in situ nutrient sensing using electrochemical methods, representing a major step toward continuous soil health analysis. Together, these studies underline the evolution from traditional soil testing toward IoT-enabled, real-time, and data-driven soil monitoring systems that enhance precision farming and sustainable agriculture**.**

In this project, we have designed and implemented an IoT-enabled Soil Health Monitoring System aimed at improving agricultural productivity and sustainability through real-time monitoring of key soil parameters. The system continuously measures soil moisture, temperature, pH, and nutrient levels (N, P, K) using a network of sensors integrated with Arduino Nano and ESP32 microcontrollers. The collected data is transmitted wirelessly to the Blynk IoT cloud platform, where farmers and researchers can remotely access and visualize real-time soil data through a smartphone or web dashboard. To ensure energy efficiency and continuous operation in rural and off- grid areas, the system is powered by a solar-charged 12V battery, making it eco-friendly and cost-effective. Calibration and testing were carried out under real agricultural conditions, and results showed high accuracy and stability in sensor readings compared to traditional methods. This project not only integrates multiple sensors into a single compact unit but also leverages artificial intelligence and IoT technologies to support precision farming, enabling optimized irrigation, fertilizer management, and resource utilization. The innovative design promotes environmental sustainability, reduces human effort, and provides a scalable and affordable solution for farmers to maintain soil fertility, increase crop yield, and contribute to the vision of smart and sustainable agriculture.

Thus, the present paper proposes a method of measuring soil moisture, pH, temperature and NPK nutrients using industrial sensors.

II. METHODOLOGY

In this research, the system measures key soil parameters like moisture, temperature, pH, and NPK (Nitrogen, Phosphorus, Potassium) in real time. It includes two microcontrollers: an Arduino Nano for collecting sensor data and an ESP32 for wireless communication. Both are powered by a 12V rechargeable battery with support from a solar panel for eco-friendly operation. The NPK sensor operates at 12V. The other components, including the Arduino Nano, ESP32, and remaining sensors, work at 5V through a voltage regulator, specifically a buck converter. The Arduino Nano gathers and processes data from all sensors and sends it via serial communication to the ESP32. The ESP32 then transmits the data wirelessly to the Blynk IoT platform using its built- in Wi-Fi. On the Blynk app, users can view real-time soil data through gauges and see values. Alerts can also be triggered whenever parameters exceed the desired range. The system was tested in soil and consistently provided stable readings, demonstrating its reliability, energy efficiency, and suitability for smart, sustainable agricultural practices. Figure 1 below shows the schematic block diagram of the system.

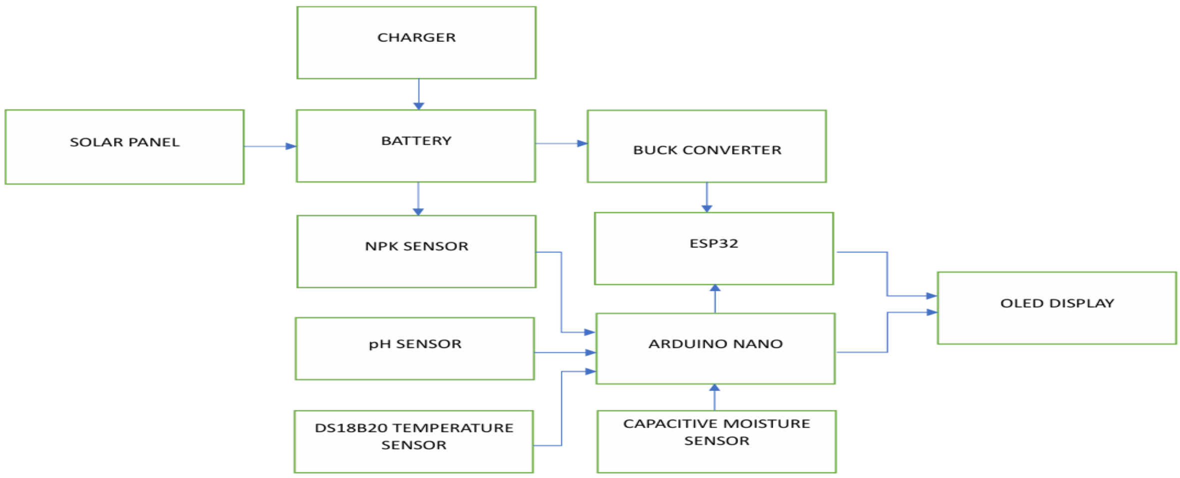

Fig.1: Block diagram

III. COMPONENTS

- **ESP-32:** The ESP32 is a powerful microcontroller with built-in Wi-Fi and Bluetooth capabilities. In this project, it is used for wireless data transmission. It receives processed data from the Arduino Nano via serial communication (TX–RX) and uploads it to the Blynk IoT cloud for real-time monitoring through a smartphone or web dashboard.

Fig.2 ESP-32

Arduino Nano: The Arduino Nano is a compact and cost-effective microcontroller board based on the ATmega328P. It is used as the main control unit in the system to read data from various analog and digital sensors such as the moisture, pH, temperature, and NPK sensors. Its small size, low power consumption, and multiple analog pins make it ideal for embedded sensing applications.

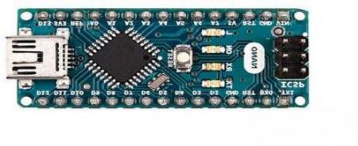

Fig.3 Arduino Nano

- **NPK Sensor:** The NPK sensor measures soil nutrients — Nitrogen (N), Phosphorus (P), and Potassium (K) — essential for plant growth. It operates at 12V and communicates with the Arduino Nano via an RS485 module, ensuring stable and accurate data transmission. The sensor provides real-time nutrient values that are sent to the ESP32 for display on the Blynk IoT platform.
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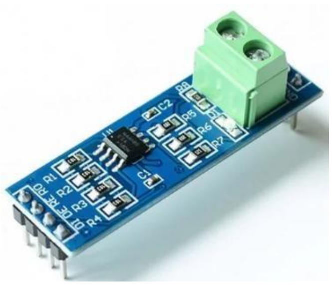

Fig.4 RS485 module **Fig.5 NPK Sensor**

- **pH Sensor:** The pH sensor measures the acidity or alkalinity of the soil, which is crucial for determining nutrient availability for plants. It provides an analog output that is read by the Arduino Nano to assess soil health and suitability for specific crops.

Fig.6 pH Sensor

- **Capacitive Moisture Sensor:** This sensor measures the water content in the soil by detecting changes in electrical resistance or capacitance. The output helps farmers determine the irrigation needs of the crop, preventing both overwatering and underwatering.

Fig.7 Capacitive Moisture Sensor

- **Temperature Sensor:** The temperature sensor monitors soil or ambient temperature, which influences root growth and nutrient uptake. The data is sent to the Arduino Nano for analysis and display through the IoT platform.

Fig.8 LM35 Temperature Sensor

- **Buck Converter:** The voltage regulator is used to convert 12V DC to 5V DC to safely power the Arduino Nano, ESP32, and low-voltage sensors. It ensures stable operation and protects the components from voltage fluctuations.

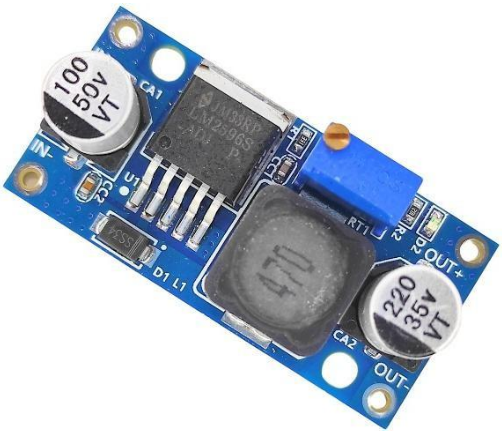

Fig.9 LM2596 Buck Converter

- **Battery:** The system is powered by a 12V battery, providing energy to the NPK sensor and other components through a voltage regulator that steps down the voltage to 5V for the Arduino and ESP32. This ensures stable and uninterrupted operation.

- **Solar Panel:** A solar panel is integrated to recharge the battery continuously, making the system self-sustaining and eco- friendly. It allows the setup to operate in remote agricultural fields without dependence on external power sources.

- **Blynk IoT:** The Blynk app serves as the user interface for real-time monitoring and data visualization. It displays the soil parameters through gauges, graphs, and indicators, and also provides instant alerts when soil conditions deviate from

optimal ranges.

- **Charger:** The battery charger is used to recharge the 12V battery that powers the entire system. It provides a stable DC output to ensure safe and efficient charging without overloading the battery. The charger works along with the solar panel and charge controller, maintaining continuous power supply to the Arduino Nano, ESP32, sensors, and OLED display for reliable system operation.

- **OLED Display:** The OLED display provides a local visual interface, showing real-time readings of soil parameters such as moisture, pH, temperature, and NPK values directly on the device. This allows on-site monitoring without needing internet connectivity or a smartphone.

III. EXPERIMENTAL SETUP

The experimental setup of the IoT-based soil health monitoring system aimed to test the real-time performance and accuracy of soil parameter measurements in the field. The setup included an Arduino Nano connected to several sensors, such as soil moisture, temperature, pH, and NPK sensors. The Arduino Nano acted as the main control unit, collecting analog data from the sensors, converting it into digital signals, and preprocessing it for transmission. The processed data was then sent through serial communication (TX-RX) to the ESP32, which managed wireless data transmission with its built-in Wi-Fi module.

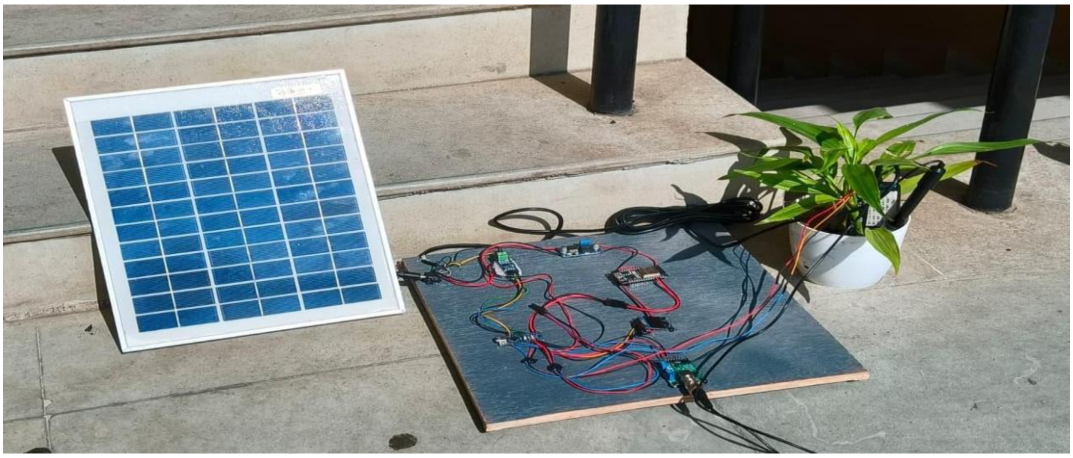

Fig.10 Experimental Setup

Above Fig.10 represents experimental setup of the system. The entire system ran on a 12V rechargeable battery. Only the NPK sensor worked at 12V, while all other components operated at 5V with the help of a voltage regulator circuit. A solar panel charged the battery, which kept everything running and improved energy efficiency during outdoor testing. The ESP32 sent the collected data to the Blynk IoT platform. Users could view the readings on a smartphone dashboard with gauges and graphs. Each parameter had a virtual pin, enabling remote monitoring of real-time soil conditions.

For field testing, the complete setup was placed in agricultural soil, and sensors were carefully inserted into the soil bed. The system continuously recorded moisture, temperature, pH, and NPK levels. These readings were compared with manual measurements to confirm accuracy. The system was reliable, delivering stable and accurate readings. It showed how effective it is to combine IoT and renewable energy for smart and sustainable soil monitoring.

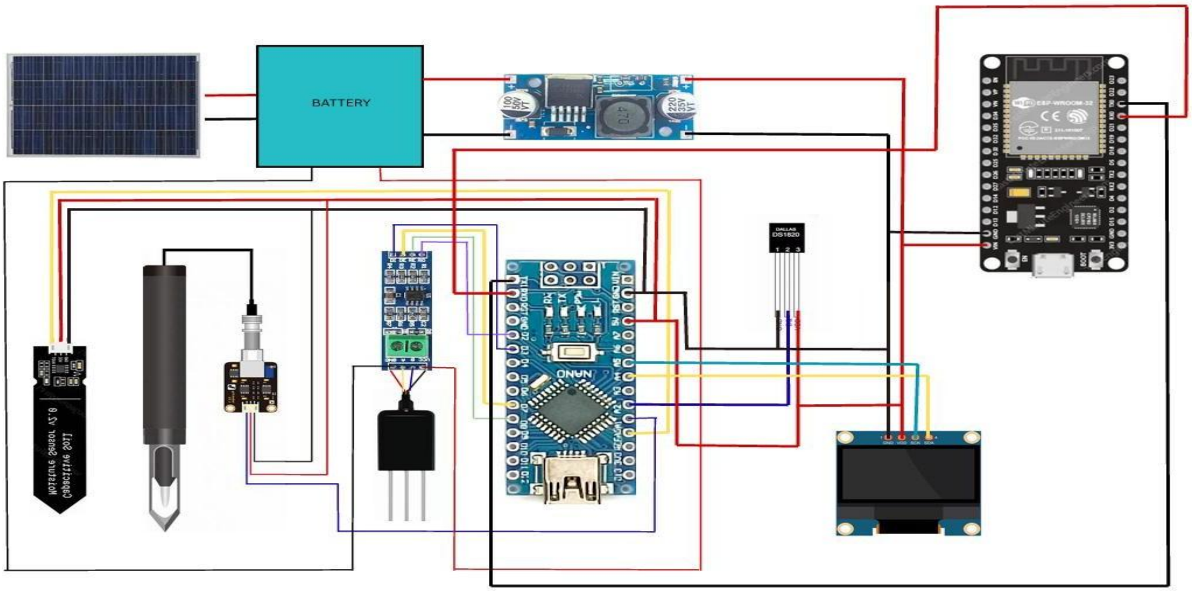

Fig.11 Circuit Diagram

The fig.11 given above shows the circuit diagram of the system. During the experiment, the sensors were carefully calibrated before data collection to ensure accurate readings. The soil moisture sensor was tested by varying the water content in the soil, and the readings on the Blynk app showed immediate changes, confirming the system's responsiveness. Similarly, the pH sensor readings were validated using standard pH solutions, while the NPK sensor results were compared with laboratory soil test reports. The results showed only minor deviations, proving that the IoT-based system could provide reliable soil information without the need for frequent manual testing. The data displayed on the Blynk dashboard was continuously updated and easy to interpret through visual widgets such as gauges and graphs, making it user- friendly for farmers and researchers alike.

The solar-powered setup worked well during the testing period. It consistently supplied power to the Arduino Nano, ESP32, and sensors, even during long outdoor use. The combination of solar energy and a 12V rechargeable battery provided continuous system performance. This shows that it is a good choice for remote and off-grid agricultural areas. Overall, the experiment showed that using IoT technology with renewable energy can offer an affordable, reliable, and sustainable way to monitor soil health in real time. This helps farmers make informed choices to boost crop productivity and manage resources better.

IV. RESULTS AND CONCULSION

The IoT-based soil health monitoring system successfully measured and transmitted real-time data on key soil parameters, including moisture, temperature, pH, and NPK (Nitrogen, Phosphorus, Potassium). The Arduino Nano collected this data, processed it, and sent it to the ESP32, which then transmitted it to the Blynk IoT platform via Wi-Fi. The readings shown on the Blynk app were consistent, responsive, and easy to understand, allowing users to monitor soil conditions remotely through their smartphones. The soil moisture sensor detected changes in irrigation levels, the pH sensor identified variations in soil acidity, and the NPK sensor provided reliable nutrient data. Comparisons from field tests with laboratory results indicated that the system had a high level of accuracy, with only minor deviations of 5 to 8 percent.

The system ran efficiently on solar power throughout the testing period, ensuring it worked continuously without needing external electricity. The 12V battery, recharged by the solar panel, supplied enough energy to power the NPK sensor and other 5V components using a voltage regulator. This confirmed the setup's sustainability and energy efficiency. Overall, the system was accurate, strong, and environmentally friendly, able to function well under different environmental conditions.

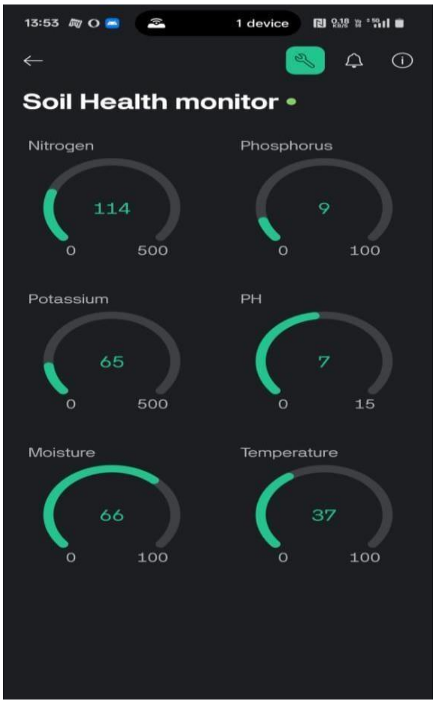

Fig.12

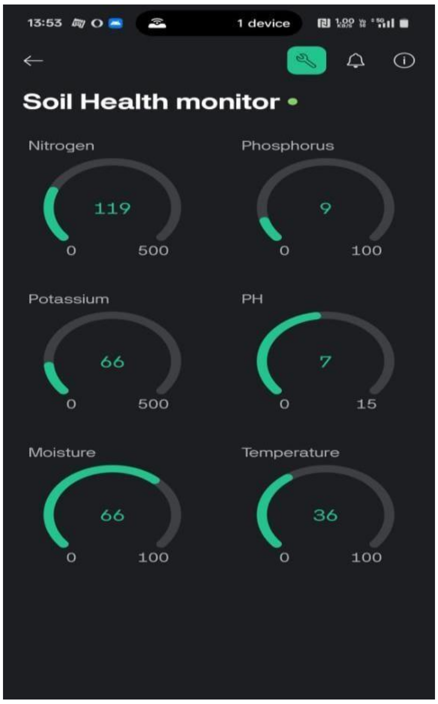

Fig.13

Fig.12 and fig.13 shows the result shown over blynk ToT platform using widgets and representing values for better and easy understanding. Furthermore, the system's connection with the Blynk IoT platform improves its usefulness by offering a real- time, easy-to-use interface that anyone can access from anywhere. Farmers and researchers can easily see data trends, set alerts for specific thresholds, and take quick actions to keep soil conditions optimal. This remote access cuts down on manual work and increases efficiency in farm management. The system's performance shows that bringing together IoT technology, renewable energy, and smart sensing creates a reliable and scalable solution for sustainable agriculture, leading to better soil health and long-term productivity.

Parameter	Sample Type	Expected Result (Reference)	Obtained Result (System)	Percentage Error (%)
Nitrogen (ppm)	Clay Soil	120	114	5.00
Nitrogen (ppm)	Clay Soil	121	119	1.65
Phosphorus (ppm)	Clay Soil	9.5	9	5.26
Phosphorus (ppm)	Clay Soil	9.5	9	5.26
Potassium (ppm)	Clay Soil	68	65	4.41
Potassium (ppm)	Clay Soil	68	66	2.94
Soil pH	Clay Soil	7.5	7	6.67
Soil pH	Clay Soil	7.5	7	6.67
Soil Moisture (%)	Clay Soil	67	66	1.49
Soil Moisture (%)	Clay Soil	67	66	1.49
Soil Temperature (°C)	All Samples	38	37	2.63
Soil Temperature (°C)	All Samples	38	36	5.26

Table 1: Comparative Results between Expected and Obtained Readings

Table 1 shows the comparative results between expected and obtained readings. In conclusion, the IoT-based soil health monitoring system demonstrates that integrating Arduino Nano, ESP32, and IoT technology with renewable energy can revolutionize agricultural practices. It enables real-time soil monitoring, promotes precision farming, and helps farmers make data-driven decisions about irrigation and fertilization. The project provides a cost-effective, scalable, and sustainable solution for improving soil management, increasing crop yield, and supporting the future of smart agriculture. The fig.14 shows the reading over oled for local reading.

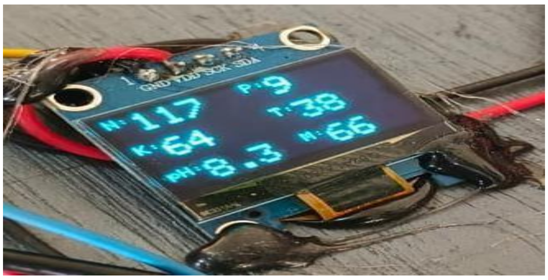

Fig.14

V. FUTURE SCOPE

In the future, the IoT-based soil health monitoring system can improve by using artificial intelligence (AI) and machine learning (ML) to analyze the data collected and give predictive insights. These technologies can forecast soil nutrient shortages, irrigation needs, and crop suitability, which allows farmers to plan their activities better. Adding advanced sensors, like humidity, rainfall, and electrical conductivity (EC) sensors, can further improve the system's accuracy and offer a clearer view of soil and environmental conditions.

The system can also upgrade to include automated irrigation and fertilization control. This would let it adjust water and nutrient supply based on real-time soil data, reducing waste and boosting crop yield through precise management. Developing a mobile or web-based platform for data visualization and report generation will enable farmers to track soil health trends over time and make informed decisions from anywhere.

Additionally, the solar power setup can improve with smart power management and tracking systems to ensure energy is used efficiently and to extend operational life in remote areas. On a larger scale, the system can expand for community or regional soil monitoring, providing valuable data for government agencies, researchers, and agricultural planners. Overall, these future advancements can turn this project into a smart, scalable, and sustainable solution that supports precision agriculture and environmental conservation.

CONFLICT OF INTEREST

The authors state that there is no conflict of interest in publishing this project. All work presented here has been done independently for academic and research purposes. No financial, personal, or professional relationships have affected the design, development, or results of the IoT-Based Soil Health Monitoring System.

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