Enhancing Agricultural Productivity with IoT-Based Soil Nutrient Monitoring and Cloud Integration

[1*]Abhishek Tripathi, [1]K Pavan Chand, [1]K Shiva Prasad, [1]C Pavan K Reddy, [1]Kothamasu Nikhil, [1]Kandregula Vanaja, [1]Chippadavardhan, [1]Kundurthi Somasekhar and [2]Mitesh Solanki

[1]Department of Computer Science and Engineering, Kalasalingam Academy of Research & Education,
Krishnankovil, Tamil Nadu, India 626126.
[2]Department of Information and Communication Technology, Marwadi University, Rajkot
*[1]tripathi.abhishek.5@gmail.com, 9921004374@klu.ac.in, 9921004907@klu.ac.in, 9921004667@klu.ac.in, 9921004116@klu.ac.in, hanumann924@gmail.com, vardhanchippada04@gmail.com, sekhersomak@gmail.com, miteshbhai.solanki@marwadieducation.edu.in.

Abstract- Addressing the urgent need for sustainable agricultural practices in response to global population growth, this study introduces a sophisticated Soil Health Monitoring System and Land Management solution, powered by cloud server technology. This system integrates an array of IoT devices, including pH sensors, soil moisture sensors, DHT11 sensors for temperature and humidity, and NPK sensors, all connected through the NodeMCU ESP8266 microcontroller. These sensors continuously monitor essential soil parameters such as moisture content, pH levels, temperature, humidity, and nutrient levels of Nitrogen, Phosphorus, and Potassium. The data collected is relayed in real-time to a centralized cloud server, ensuring immediate data availability for analysis. An intuitive web application provides farmers access to up-to-date soil health data, enabling informed decision-making on nutrient management and irrigation practices. The system also delivers real-time alerts and advisory services, critical for timely interventions to prevent soil degradation and optimize crop productivity. Empirical results from the initial deployment demonstrate that continuous monitoring and real-time data analytics significantly improve crop productivity and resource use efficiency. These findings confirm that this system greatly enhances soil sustainability by providing precise, actionable insights that support the maintenance of soil health and promote efficient agricultural practices.

Keywords: IoT, Soil Moisture, NPK Sensor, pH Value and Temperature.

1 Introduction

In the production of food and crops, soil health is a critical factor that directly impacts agricultural productivity and sustainability. Modern agricultural practices and environmental conditions have led to significant degradation of soil health, resulting in low crop yields and increased food security risks. Different soils contain various nutrients essential for the growth of specific crops. However, crops are often cultivated

without proper information about the nutrient requirements of the soil [1]. This mismanagement leads to the over-application or under-application of certain elements, further deteriorating soil health and causing crop failures. This project aims to develop a Soil Health Monitoring System and Land Management solution using cloud server technology, IoT devices, and soil sensors. Key soil health parameters such as moisture content, pH levels, temperature, humidity, and nutrient levels will be continuously monitored by this advanced system for real-time evaluation. By investing in this technology, farmers can make informed decisions regarding nutrient management practices, ensuring that crops receive all necessary nutrients for optimal growth while maintaining healthy soils [2].
In India, out of 157 million hectares of cultivable land, 49 million hectares are acidic. Of this, 26 million hectares have a soil pH less than 5.6, and the remaining 23 million hectares have a pH range of 5.6 to 6.5. The pH range in Indian soils is highly variable, ranging from as low as 5.0 to as high as 10.0, depending on factors like high rainfall or semi-arid to arid regions. In areas with higher rainfall, the natural pH of soils typically ranges from 5 to 7, while in drier areas, it ranges from 6.5 to 9. This variability underscores the importance of effective soil management. Agricultural lime or 'liming materials' may be added to raise pH, while elemental sulfur or acidifying materials can be used to lower pH for specific crops [3] [4].
This study highlights the benefits of regular soil monitoring and management, demonstrating significant improvements in soil pH and moisture levels. The significance of this study lies in its potential to revolutionize agriculture by providing farmers with the tools and knowledge needed to maintain optimal soil health and achieve sustainable crop production.

2 Literature Survey

Numerous The field of soil health monitoring and land management has seen significant advancements through the integration of various technologies and methodologies. Varnit Goswami (2020) developed a comprehensive Soil Health Monitoring System utilizing sensors to measure essential soil health parameters such as potassium, nitrogen, phosphorus, pH levels, and moisture content. This study demonstrated the potential of sensor technology to provide real-time data on soil conditions, enabling better management decisions for sustainable agriculture [5]. Building on the concept of real-time monitoring, Zhaoya Chen (2020) explored the application of Internet of Things (IoT) technology for the sustainable use of soil and land resources. This work emphasized the importance of IoT in rapidly acquiring land information, predicting environmental trends, and providing practical solutions to land management issues. The integration of IoT systems allows for continuous monitoring and more efficient resource use, highlighting its significance in modern agricultural practices [6]. M M Tahat (2020) reviewed the critical role of soil health in intensive crop production systems and identified key factors for sustainable agriculture. The study underlined the necessity of maintaining soil health to achieve high crop yields and sustainability. Tahat's review provided a comprehensive overview of how various practices affect soil health and the importance of sustainable management techniques in preserving soil quality for future generations [7].

Further advancing the field, SR Jino Ramson and Walter D. Leon-Salas (2021) presented a self-powered, real-time IoT-based soil health monitoring system. Their study focused on integrating biodiversity into soil quality monitoring, aiming to identify bioindicators and establish baseline values for different biological groups based on land use types. This approach offered a holistic view of soil health, considering both chemical and biological indicators, and emphasized the importance of biodiversity in soil monitoring [8]. Fiona M. Seaton and Gaynor Barrett (2021) conducted a soil health cluster analysis based on national monitoring of soil indicators. Their research used two methods to determine soil values, comparing them with European studies to highlight differences in soil properties across various habitats. The study underscored the importance of land-use management in determining soil health and function, demonstrating how different management practices can influence soil quality and sustainability [9].

Collectively, these studies provide a robust foundation for the current project, which aims to develop a Soil Health Monitoring System and Land Management solution using cloud server technology, IoT devices, and soil sensors. By leveraging the insights from previous research, this project seeks to offer a comprehensive tool for farmers to monitor soil health parameters continuously, make informed decisions on nutrient management, and ensure sustainable agricultural practices.

3 Proposed Methodology

The Soil Health Monitoring System introduced in this project utilizes a robust blend of hardware components and IoT technology to effectively monitor and manage soil health. It features a comprehensive system architecture that integrates specialized IoT devices such as a pH sensor, a soil moisture sensor, a JXCT NPK sensor, and a DHT11 sensor for measuring temperature and humidity. These devices are all connected to a NodeMCU ESP8266 microcontroller, which acts as the central unit for data collection. Programmed using the Arduino IDE, the microcontroller captures and preprocesses data from these sensors at set intervals to ensure enhanced accuracy and reliability. This connectivity is illustrated in the block diagram of Fig. 1, which shows data flow starting from the sensors to the NodeMCU ESP8266, and then onto the cloud server. The server processes and stores the data, making it available through a web application for real-time monitoring and management, thereby facilitating effective soil health oversight.

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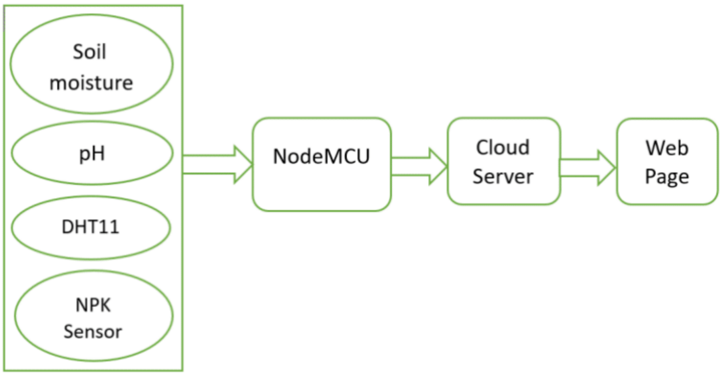


Fig. 1. Block diagram of system architecture.

The flowchart provides a step-by-step algorithm of the system's operation, beginning with data input through the sensors. The NodeMCU collects and processes these inputs, which are then displayed on the webpage. If the data is successfully transmitted and no further updates are required, it displays the result directly. Otherwise, it reconnects to the server for the latest data updates, ensuring continuous and up-to-date information availability for users.

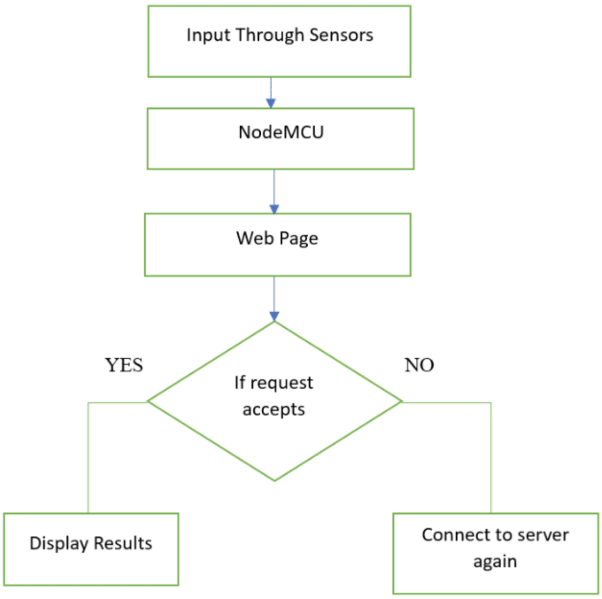


Fig. 2. Algorithm flowchart.

The methodology also includes comprehensive system testing to ensure accuracy and reliability. The sensors undergo rigorous calibration and field testing in various soil types and environmental conditions to validate their performance. Additionally, user training sessions and support systems are established to help farmers understand and utilize the web application effectively, maximizing the benefits of the monitoring system. Costs include IoT hardware, cloud infrastructure, and installation, with additional expenses for maintenance, connectivity, and farmer training. Operational sustainability also requires long-term investment in system upkeep.

4 System Implementation

Data from the sensors is then wirelessly transmitted to a centralized cloud server through the NodeMCU's Wi-Fi capability. This cloud server is configured to receive, store, and manage the data efficiently, providing a scalable platform for robust data handling. A web-based application developed as part of this system offers real-time access to the monitored soil health data. This application provides a user-friendly interface where farmers can log in to view detailed visualizations of soil parameters in the form of graphs and charts. These visualizations display trends and patterns that aid farmers in making informed decisions regarding soil and crop management.

Fig. 3 presents a Tinkercad simulation layout illustrating the operational blueprint of the soil health monitoring system. It visually represents the integration and interaction of various IoT components as simulated for testing the theoretical functionalities before real-world application.

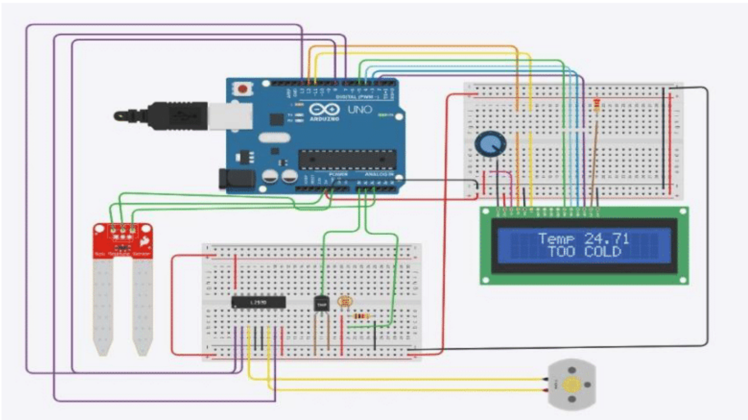


Fig. 3 Simulation layout of IoT-based soil health monitoring system in Tinkercad.

Fig. 4 showcases the actual hardware setup connected to a laptop and positioned within a soil tray. This setup is used for the practical testing and validation of the system, ensuring that all components function cohesively in a controlled environment to simulate field conditions.

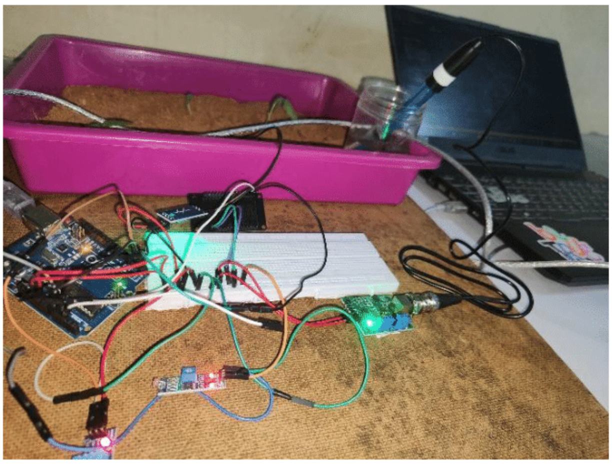
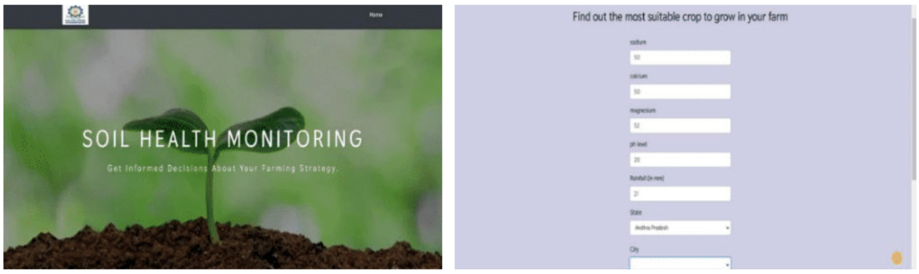
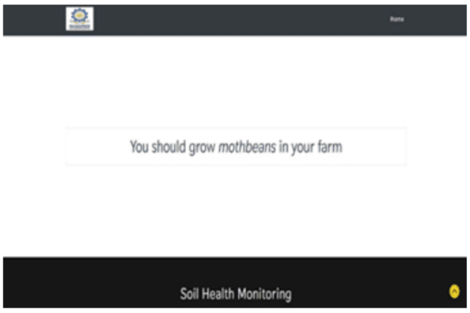


Fig. 4 Implementation of testbed for soil health monitoring system.

Fig. 5 features three sub-figures displaying the developed web application, which reflects real-time soil health data and provides user interactions. Sub-figure (a) shows the homepage with the KARE university logo, (b) displays a form requesting inputs such as sodium, calcium, magnesium levels, soil pH, average rainfall, and geographical region, and (c) illustrates the output page offering crop recommendations based on the inputted soil conditions.



(a) (b)



(C)

Fig. 5 Interface of the web application for soil health monitoring (a) Homepage with KARE logo, (b) Soil input form and (c) Crop recommendations.

In the proposed Soil Health Monitoring System, the initialization phase includes loading the necessary DHT library and setting up constants for the DHT11 sensor to monitor temperature and humidity, as well as distinct analog pins for the soil moisture, LDR (light intensity), and JXCT NPK sensors for monitoring essential soil nutrients. During setup, serial communication is initiated at 9600 bps, and all sensor pins are configured as inputs to prepare for data collection. In the main loop, the system incorporates a brief pause to maintain proper timing between sensor readings. The DHT11 sensor measures ambient temperature and humidity, and analog readings are taken from the soil moisture, LDR, and NPK sensors on their respective pins to assess moisture levels, light intensity, and nutrient content accurately. If any sensor data is invalid, an error message is generated, skipping the current loop iteration to ensure data integrity. Valid sensor readings are then output to the serial console in a readable format and formatted as CSV strings for potential data logging, providing real-time, precise data that is crucial for making informed agricultural decisions. It provides a comprehensive overview of the technical workflow and data handling process of the Soil Health Monitoring System, showcasing its efficiency in real-time data monitoring and soil health management.
Scaling the system to real-life settings may face challenges such as soil variability affecting sensor accuracy, weather conditions impacting sensor durability, unreliable internet connectivity in rural areas, and inconsistent power supply disrupting data transmission and monitoring. Addressing these challenges requires robust sensor calibration, durable hardware, and alternative power and communication solutions.

5 Results and Discussion

Fig. 6 compares the levels of Nitrogen (N), Phosphorus (P), and Potassium (K) in soil before and after monitoring. The nutrient levels were adjusted using fertilizers such as

Urea, diammonium phosphate (DAP), and potash or to achieve a possible balanced ratio of 4:2:1 for rice crop, which is optimal for promoting healthy plant growth and high yields.

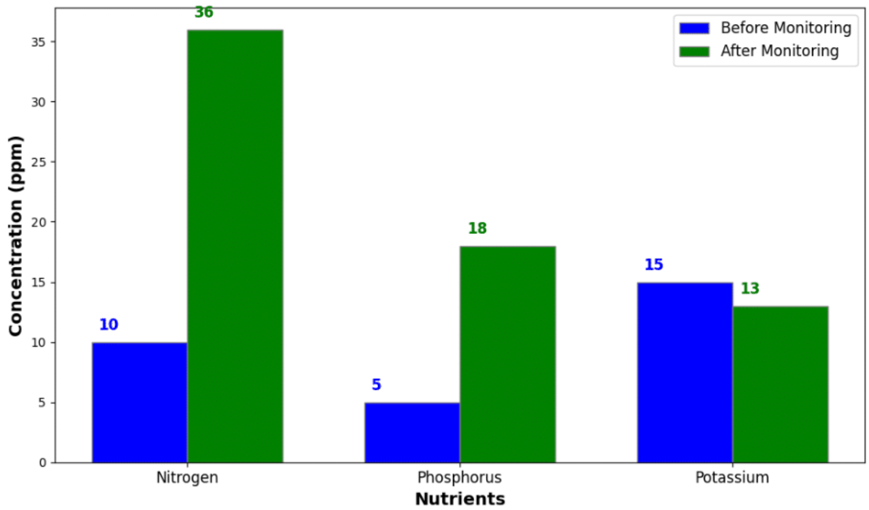


Fig. 6. Soil nutrient levels before and after monitoring.

Fig. 7 compares soil pH levels over one week with and without monitoring. Without maintaining, the soil pH levels fluctuated between 7.8 and 8.3, indicating an alkaline condition that can limit the availability of essential nutrients to plants. With maintaining, the soil pH levels were consistently maintained between 6.4 and 6.8. This reduction in pH was achieved through the application of acidifying materials such as elemental sulfur. Regular monitoring allowed for timely adjustments to keep the pH within the optimal range (5.6 to 6.5) for most crops, promoting better nutrient availability and plant growth.

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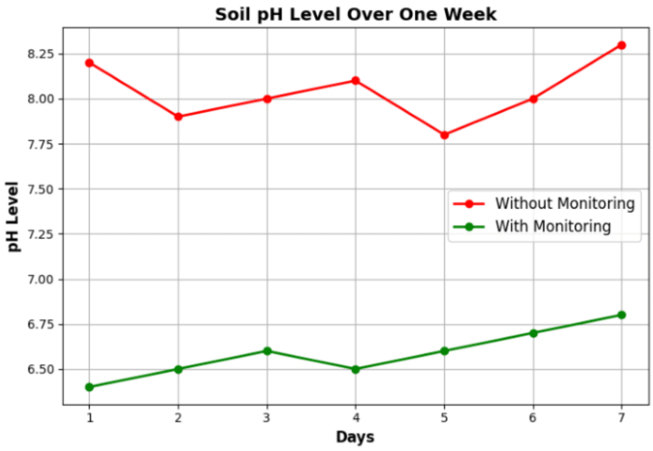

Fig. 7. Effect of monitoring on soil pH levels over one week.

Fig. 8 compares soil moisture levels over one week with and without monitoring. Without maintaining, the soil moisture levels decreased significantly from 38% to 17% over the week, indicating inadequate water retention and potential drought stress, which can adversely affect plant health and yield. With maintaining, the soil moisture levels were consistently maintained between 38% and 43%. This stability was achieved through the use of micro-irrigation techniques, ensuring that the soil retained adequate moisture levels. Regular monitoring enabled precise water management, reducing water stress and promoting healthy crop growth.

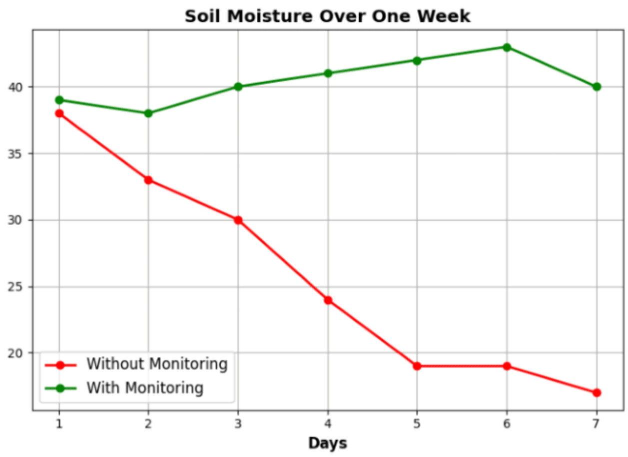

Fig. 8. Effect of maintaining on soil moisture levels over one week.

Fig. 6, 7, and 8 show measurable improvements in soil nutrients, pH, and moisture, directly supporting the system's effectiveness in optimizing soil health and improving crop productivity. These results reinforce the argument for real-time monitoring.

6 Conclusion

The proposed Soil Health Monitoring System leverages cloud server technology, IoT devices, and advanced soil sensors to provide a real-time, efficient, and scalable solution for comprehensive monitoring of soil health parameters, including soil moisture, pH levels, and crucial nutrients such as Nitrogen, Phosphorus, and Potassium. By integrating pH sensors, soil moisture sensors, NPK sensors, and DHT11 sensors with the NodeMCU ESP8266 microcontroller, the system continuously collects and transmits a broad spectrum of soil data to a centralized cloud server. This rich dataset is then accessible through an intuitive web application, empowering farmers with the necessary tools to make informed decisions regarding nutrient management and irrigation practices. The system not only offers real-time early warnings and advisory services to prevent soil degradation and enhance crop productivity but also facilitates the analysis of historical data to support long-term soil health management. This makes the system a pivotal tool for sustainable agriculture. With extensive testing and targeted user training, the system is designed to be both reliable and user-friendly, ensuring its easy adoption by farmers eager to optimize their agricultural practices.

7 Future Work

Future scope will focus on integrating advanced data analytics and AI algorithms, incorporating remote sensing technologies like satellite imagery and drones, and expanding the sensor network to include soil salinity and organic matter content. Developing a mobile application will increase accessibility, and integrating automated irrigation systems will optimize water use. Engaging with local agricultural communities and conducting environmental impact assessments will further enhance the system's effectiveness and sustainability. By addressing these areas, the Soil Health Monitoring System can better benefit farmers and contribute to more sustainable agricultural practices globally.

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