Sensor-Based IoT Framework for Real-Time NPK Analysis and Improved Crop Production

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Abstract: Soil fertility is a critical factor in ensuring healthy crop growth and agricultural productivity. Traditional methods of assessing soil fertility, which rely on laboratory testing to measure essential nutrients like Nitrogen (N), Phosphorus (P), and Potassium (K), are often time-consuming, labor-intensive, and impractical for small-scale farmers. To address these challenges, this paper proposes an advanced framework that combines Internet of Things (IoT) technology with an optical transducer for efficient soil fertility analysis. The optical transducer measures the absorption of light by soil, accurately detecting the presence and levels of N, P, and K. IoT-enabled sensors monitor additional parameters, such as pH, temperature, and moisture, providing comprehensive real-time data. This data is transmitted to farmers, enabling them to make timely and informed decisions regarding fertilizer application. The proposed system eliminates the need for laboratory testing, offering a faster, more cost-effective solution. By accurately identifying nutrient deficiencies and minimizing fertilizer overuse, this technology helps preserve soil health, improve crop yields, and promote sustainable farming practices. The integration of IoT and optical sensing technology represents a promising innovation in agriculture, enhancing productivity while reducing environmental impact.

Keywords- Soil Fertility, IoT, Optical Transducer, Nutrient Detection, Sustainable Agriculture, Fertilizer Management, Real-Time Monitoring, Agricultural Technology.

1. INTRODUCTION

The Internet of Things is a network of interconnected physical devices that are internet-connected and can gather, transmit, and receive data without human intervention. They are equipped with sensors, software, and communication technologies, enabling them to sense their surroundings and communicate with other systems or users. In farming, IoT has an important role to play by facilitating real-time monitoring and analysis of multiple parameters like soil moisture, temperature, and nutrient content. For instance, an IoT-connected soil sensor can determine vital nutrients like Nitrogen (N), Phosphorus (P), and Potassium (K) and send that information to a farmer's mobile device or cloud console in real- time. This enables farmers to take well- informed decisions regarding the application of fertilizer, irrigation, and crop care, resulting in enhanced efficiency, cost savings, and better yields. Overall, IoT connects the physical and digital worlds, and hence, smart and sustainable modern farming.

Internet of Things (IoT) is defined as a collection of physical devices, sensors, and machines embedded with electronics, software, and network connectivity to sense, collect, send, or act on data over the internet. In the past few years, IoT has been a revolutionary technology in many fields, particularly in agriculture, where it has set the stage for what is currently referred to as smart farming or precision agriculture.

In traditional farming, decisions related to irrigation, fertilization, and crop treatment are usually made based on manual observation, historical data, or guesswork. This can lead to inefficient resource utilization, irregular crop yields, and long-term soil degradation. IoT changes this scenario by providing real-time monitoring

and data-driven decision-making. With sensor networks, IoT enables farmers to collect essential field information like soil moisture, NPK levels (nutrient), temperature, pH, and humidity. The sensors are linked with microcontrollers (such as the Node MCU ESP8266), which process data and pass it to a cloud platform for storage and analysis. Farmers can see this data in real time, get alerts, and make decisions in time through a basic mobile or web application. The Internet of Things (IoT) is transforming agriculture by providing real-time monitoring, data gathering, and decision-making capabilities with the help of networked intelligent devices. IoT, in the context of contemporary agriculture is a potent means of precision farming that provides farmers with profound information about environmental and soil conditions, which were previously hard to observe continuously and with accuracy. This project utilizes IoT technology to conduct real-time soil fertility analysis through the measurement of the Nitrogen (N), Phosphorus (P), and Potassium (K) concentrations the three main nutrients essential for plant growth. By implementing intelligent NPK sensors, microcontrollers, and wireless communication modules, the system acquires and sends soil data to cloud platforms or mobile devices for analysis and visualization.

2. LITERATURE SURVEY

R.V.B. Paulino et al., "Applications of laser-induced breakdown spectroscopy for soil characterization, part II: Review of elemental analysis and soil classification," European Journal of Soil Science, vol. 71, no. 5, pp. 805-818, 2019.

This paper reviews the applications of Laser-Induced Breakdown Spectroscopy (LIBS) in soil analysis. The authors discuss how LIBS is used for elemental analysis and soil classification, highlighting its ability to rapidly analyze the composition of soils, which aids in soil characterization for agricultural and environmental purposes.

P. Srivastava, A. Shukla, and A. Bansal, "A comprehensive review on soil classification using deep learning and computer vision techniques," Multimedia Tools and Applications, pp. 1-28, 2021.

This paper provides an extensive review of how deep learning and computer vision techniques have been applied to soil classification. It focuses on the use of image-based classification methods and neural networks for analyzing soil properties, contributing to automation in soil management and precision agriculture.

F.M. Seaton et al., "Soil health cluster analysis based on national monitoring of soil indicators," European Journal of Soil Science, 2020.

This research discusses the use of cluster analysis to assess soil health based on national monitoring of soil indicators. The authors analyze various soil health metrics and use statistical methods to group soil types based on their health status, which can help guide soil management strategies.

A. Benedet et al., "Soil subgroup prediction via portable X-ray fluorescence and visible near-infrared spectroscopy," Geoderma, vol. 365, art. 114212, 2020.

This study explores the use of portable X-ray fluorescence (XRF) and visible near-infrared (VIS-NIR) spectroscopy for predicting soil subgroups. These methods enable rapid, in-situ soil analysis without the need for traditional laboratory-based techniques, making soil classification more efficient and accessible in field conditions.

A. Plowcha et al., "Online soil classification using a UAS sensor emplacement system," Springer, pp. 174-184, 2020.

This paper presents a system for online soil classification using unmanned aerial systems (UAS). The authors describe how UAS equipped with sensors can capture soil data and automatically classify soil types in real-time, offering a more efficient and scalable solution for large-scale soil mapping.

K.S. Yin et al., "Marine soil behavior classification using piezocone penetration test (CPT) and borehole records," Canadian Geotechnical Journal, vol. 58, no. 2, pp. 190-199, 2021.

This research focuses on classifying marine soil behavior using piezocone penetration tests (CPT) and borehole records. The study highlights how these geotechnical tests can be used to evaluate soil properties like stiffness, strength, and stratigraphy in marine environments, which are critical for coastal engineering and construction projects.

P.C. J. Priyanka et al., "An analytical approach for soil and land classification system using machine learning," International Journal of Scientific Research in Science, 2020.

This paper introduces an analytical approach to soil and land classification using machine learning techniques. It discusses how algorithms like decision trees and support vector machines can be applied to classify soil based on various features, providing a data-driven approach to land management.

3. PROPOSED SYSTEM

The Real-Time IoT-Based Soil Fertility Analysis System proposed hereby is a novel, technologically integrated approach to enabling smarter, more efficient agriculture. The system is aimed at overcoming the shortcomings of conventional soil testing techniques by making use of advanced digital resources and automation. Fundamentally, the system integrates IoT sensors, cloud computing, real-time processing of data, and simple interfaces to give farmers usable intelligence about soil conditions, specifically targeting precise measurement of macronutrients like Nitrogen (N), Phosphorus (P), and Potassium (K), and pH, moisture, and temperature. Such active monitoring allows for well-informed decision-making, resulting in improved crop yields, optimized fertilizer application, and sustainable soil practices.
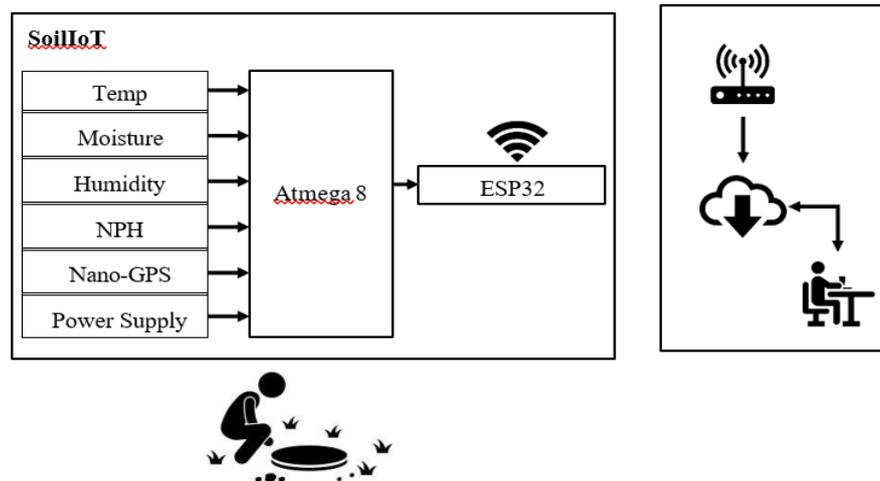

**FIGURE 1.** The System Architecture.

An integral part of this system is the use of IoT-based soil sensors. These sensors are strategically located in the field to monitor significant soil parameters in real time. The data thus obtained is sent wirelessly to a central processing unit, minimizing manual soil sampling and regular on-site visits. Automated collection of data, through the system, provides accurate and timely deficiencies detection, enabling prompt intervention and minimizing crop loss due to impaired soils. In order to particularly examine the NPK content in the soil, the system utilizes an optical transducer-based sensing mechanism. The technology is based on measuring the light absorption at certain wavelengths that correspond to nitrogen, phosphorus, and potassium. The optical transducer is able to sense minute changes in light intensity as it interacts with soil samples, converting these changes into quantifiable nutrient concentrations. It is quick, accurate, and can provide immediate readings, making it an excellent replacement for traditional chemical testing methods. Optical sensing integration guarantees farmers highly accurate nutrient information, which is essential in determining the exact type and amount of fertilizer needed.

For user interaction, the system provides simple-to-use web and mobile interfaces tailored for farmers. The

websites offer real-time visualization of soil information, advice for the application of nutrients, weather forecasts, and monitoring of crop performance. The user interface is intuitive and straightforward in order to make it easy for even less computer-literate farmers to use the system. This ease of access allows more users to embrace smart agriculture techniques and enjoy precision farming without the necessity for broad technical education. Aside from increasing productivity, the suggested system has a strong focus on sustainability and environmental protection. Through the accurate use of fertilizers in accordance with real-time data on the soil, the system minimizes the overuse and leaching of chemicals, which are significant causes of water pollution and soil erosion. It also maximizes resource-conserving agriculture through optimized irrigation timetables and minimized use of energy. Such sustainable practices help both the farmer personally but also preserve farmland in the long term, preserve biodiversity, and the balance of ecology.

4. RESULTS AND DISCUSSION

The IoT-based soil fertility monitoring system proposed in this project effectively combines NPK sensors, pH sensors, soil moisture sensors, and environmental sensors with a microcontroller (ESP8266 NodeMCU) to enable real-time soil analysis. The system was tested in realistic field conditions, and the outcome showed its potential to capture essential soil health parameters. The NPK sensor precisely reported the concentration of the critical macronutrients— Nitrogen (N), Phosphorus (P), and Potassium (K)—in real-time. These data were readily viewable on a user-friendly web platform, enabling farmers to keep an eye on soil fertility and intervene in time to correct the deficiency. Moreover, the pH sensor enabled measuring the soil's alkalinity or acidity, yielding vital information on selecting crops and the application of fertilizer. The platform also features a complete historical record of soil readings. Data accumulated over time are presented in tabular format, with parameters like pH, temperature, humidity, NPK values, and soil moisture, all reported with accurate date and time stamps. The historical data allow farmers and agronomists to track changes and trends in soil conditions, evaluate the effect of treatments or fertilizers applied, and make decisions for future farming activities. Regular monitoring allows long-term soil health to be sustained and even improved. The time-based view provides an engaging additional dimension of analysis, allowing the user to view not only current conditions, but how their land evolves over weeks or months. To increase field-level responsiveness, the system enables farmers to personalize alerts by defining threshold levels for temperature and soil moisture, and their mobile contact details. When soil moisture drops below or temperature goes above the defined limits, the system sends an automatic alert — perhaps through SMS or app notification. This real-time alert system enables farmers to take preventive measures like irrigating their fields or applying mulch before crop stress. Particularly in remote locations or harsh weather conditions, this facility acts as a critical communication bridge between land and farmer, enabling timely intervention and minimizing the likelihood of yield loss.
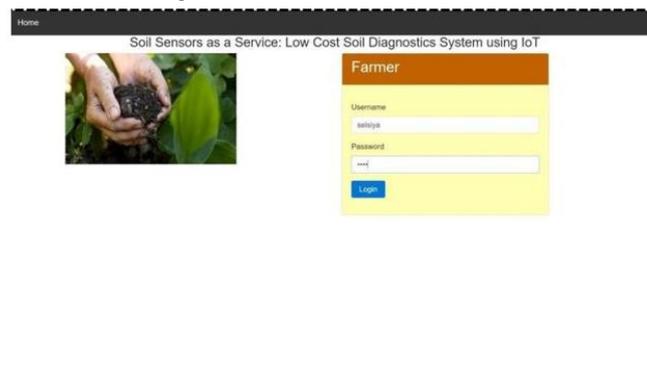
5. CONCLUSION

In conclusion, the Real-Time IoT-Driven Soil Fertility Analysis project is set to transform modern agriculture by integrating advanced IoT technology and optical sensors for accurate, real-time soil monitoring. This system empowers farmers to make data-driven decisions by providing detailed insights into essential soil nutrients such as Nitrogen, Phosphorus, Potassium, pH, moisture, and temperature. The ability to instantly detect nutrient deficiencies and optimize fertilizer usage ensures better crop yields and more sustainable farming practices. For farmers, the system offers an easy-to-use interface that provides actionable fertilizer recommendations, reducing the need for costly and time-consuming laboratory testing. The real-time data transmission and cloud-based infrastructure further enhance the system's scalability and adaptability, allowing it

to meet the diverse needs of different farming environments. The integration of IoT and real- time alerts helps farmers act quickly to rectify soil imbalances, preventing over- fertilization and promoting soil health. Ultimately, this project represents a significant step forward in agricultural innovation, helping farmers increase productivity, reduce costs, and foster sustainable practices. By leveraging cutting- edge technology, the system plays a key role in improving global food security while promoting environmental stewardship.

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