

A Sensor-Based Soil Monitoring System for Better Crop Harvesting

Kajal Shinde^{1,*}, Ayush Vishwakarma¹, Shivam Wayal¹, Shweta Thorat¹

Abstract

Crop productivity is strongly affected by soil health, environmental conditions, and the availability of timely and accurate monitoring data. Traditional soil testing and crop assessment methods are labor-intensive and time-consuming. They also lack real-time capabilities, which limits efficient agricultural decision-making. This paper proposes an IoT-enabled smart soil monitoring and crop management system that provides real-time analysis of important soil and environmental parameters to improve agricultural productivity. The proposed system uses a network of sensors to continuously monitor key soil properties, including moisture content, pH level, and macronutrient concentration (NPK). An ESP32 microcontroller processes the collected sensor data and sends it to a cloud-based platform via GSM communication. This ensures reliable data access even in remote agricultural areas. The system runs on solar energy and uses efficient buck and step-up DC-DC converters. This design allows for continuous operation with low power consumption and better energy sustainability. Additionally, an ESP32-CAM module is included to support real-time visual crop monitoring. This feature enables early detection of pests, plant diseases, and growth issues through image analysis. It provides timely alerts, allowing farmers to take preventive measures and minimize potential crop losses. Experimental evaluation shows that the proposed system greatly improves soil health assessment, irrigation scheduling, and nutrient management. The real-time data visualization and analytical insights help farmers make informed decisions, leading to better resource use, increased crop yield, and lower operational costs. The results indicate that IoT-based precision agriculture systems can significantly foster sustainable farming practices and enhance overall agricultural productivity and long-term agricultural sustainability.

Keywords: ESP32, harvesting, IoT, NPK, solar energy, sustainability

INTRODUCTION

Agriculture forms the pillar of numerous economies, ensuring food security and raw material supply to industries across the globe. But volatile environmental factors, land degradation, and poor agricultural practices are huge challenges to crop productivity. Soil health determines crop output, and early intervention supported by reliable soil analysis can avert losses and improve productivity [1]. Traditional soil testing methods entail periodic sampling and laboratory testing, which are costly, time-

consuming, and do not have real-time monitoring the arrival of the Internet of Things (IoT) has transformed precision farming by making it possible to monitor soil automatically using sensor networks. IoT solutions make it easy to collect data continuously, access it from anywhere, and make smart decisions in real time – something traditional methods just can't match. This study suggests a sensor-based soil monitoring system that utilizes multiple sensors to detect soil moisture, pH, and nutrient content. The system is driven by a solar power source and incorporates GSM communication to give farmers real-time

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information on soil conditions [2]. Moreover, an ESP32-CAM module with an automated mechanized rod takes real-time photos of crops to identify possible threats, including pests and fungal diseases.

This paper addresses the design, implementation, and efficacy of the suggested system, noting its potential to enhance agricultural productivity, lower input costs, and encourage sustainable farming. Through the use of real-time data analytics and remote monitoring, the system enables farmers to make better-informed decisions, optimize irrigation timetables, and improve soil fertility, leading to improved crop harvesting results [3].

OBJECTIVES

- *To Enable Real-Time Soil Monitoring for Informed Decision-Making:* The goal is to give farmers continuous access to key soil parameters like nitrogen, phosphorus, potassium, and moisture. By providing instant insights, it helps them make timely decisions that improve crop health and yield.
- *To Integrate Early Pest Detection Through On-Site Image Capture:* The system aims to identify potential pest threats early using a built-in camera. This allows farmers to take preventive measures before infestations spread, minimizing crop damage and losses [4].
- *To Deliver Crop-Specific Recommendations Based on Soil Data:* A core objective is to offer actionable advice tailored to each crop. The system compares live sensor readings with ideal crop requirements and suggests precise corrections, helping farmers avoid guesswork.
- *To Ensure Reliable Operation in Rural and Low-Connectivity Areas:* Designed for remote farms, the system includes Bluetooth and SMS features alongside internet connectivity. This ensures consistent performance even where internet access is limited or unavailable.
- *To Develop a Sustainable, Self-Powered Monitoring Solution:* By using solar power and smart battery management, the system is built to run independently. This objective supports continuous monitoring without dependence on grid electricity or frequent recharging.
- *To Simplify Soil Health Management Through a User-Friendly Mobile App:* The system includes an intuitive app that allows users to monitor data, capture images, and receive suggestions with ease. This makes soil management more accessible, even for farmers with limited tech experience [5].

METHODOLOGY

System Overview

The system is an IoT-based agricultural monitoring solution designed for soil health analysis and automated crop monitoring. It operates on solar power and transmits data via GSM to ensure functionality in rural areas.

System Components and Construction

Power Management System

To enable off-grid operation, the system uses a solar panel and a LiFePO₄ (Lithium iron phosphate) battery with efficient voltage regulation.

- *5A Buck Converter (Step-Down Mode):* Steps down 6V from the solar panel to 3.3V for safe LiFePO₄ (Lithium iron phosphate) battery charging.
- *TP5000 Charger Module:* Manages the charging process and prevents overvoltage [6].
- *Lithium Battery Protection Board (3.2V):* Protects against overcharging, over-discharging, and short circuits.

Soil Monitoring System

- The system uses three essential sensors to monitor soil health in real time
 - *Soil Moisture Sensor:* Tracks the water content in the soil to help fine-tune irrigation and prevent over- or under-watering.
 - *NPK Sensor:* Measures key nutrients – Nitrogen, Phosphorus, and Potassium – in the soil. Since it runs on 9V, a step-up converter (XL4009) is used to boost the standard 3.3V supply, making it a budget-friendly and efficient power solution.
 - *pH Sensor:* Gauges the soil's acidity or alkalinity, helping determine whether the conditions are right for specific crops [7].

Automated Crop Monitoring System

The system integrates an ESP32-CAM module for detecting pests and fungal infections.

- *ESP32-CAM Module*: Captures real-time images of crops.
- *Mechanized Rod System*: Controlled by ESP32, extending the camera when needed for field analysis.

Data Transmission & Communication

Since the system is designed for rural areas with limited internet, it relies on GSM and RS485 communication.

- *GSM Module*: Sends SMS alerts to farmers with soil health updates.
- *MAX485 TTL to RS485 Converter*: Ensures long-distance, stable sensor communication with minimal data loss.

BMS Module (Battery Management System)

This crucial module ensures the safe and efficient operation of battery packs. It incorporates protection ICs to prevent overcharging, discharging, and overcurrent conditions. Balancing circuits are included to equalize the voltage of individual cells, and MOSFETs are used for switching and load cutoff. An NTC thermistor is often present for temperature monitoring [8].

Detailed Explanation of System Components

- *NPK Sensor*: This sensor measures nutrient levels in soil using electrodes or probes to detect ion concentrations of nitrate (NO_3^-), phosphate (PO_4^{3-}), and potassium (K^+). It incorporates a microcontroller for analog-to-digital signal conversion and a communication interface such as UART, I2C, or RS485 for data transmission.
- *TP5000 Module (LiFePO4/Li-ion Charging Module)*: This charging module is based on the TP5000 chip and is built to handle a range of lithium-based batteries. It features a compact design that includes an inductor for efficient buck-mode charging, along with clearly labelled input and output terminals. Built-in indicator LEDs provide real-time charging status, while onboard resistors help manage and monitor both voltage and current levels for safe and reliable performance.
- *XL6009 Module (Boost Converter)*: This step-up voltage converter uses the XL6009 integrated circuit. Key components include an inductor for energy storage, a Schottky diode for rectification, and feedback resistors to set the output voltage, which can be adjusted using a potentiometer.
- *RS485 to TTL Module*: This module helps to form communication between RS485 and TTL UART levels. It is based on ICs like the MAX485 and includes termination resistor to prevent signal reflections and direction control pins for managing data flow.
- *Moisture Sensor (Capacitive or Resistive)*: This sensor detects soil moisture levels using either an electrode pair (resistive) or capacitor plates (capacitive). It often includes a comparator or amplifier circuit to provide an analog output corresponding to the moisture level, and it has pins for interfacing with a microcontroller [9, 10].

WORKING PRINCIPLE

Working of the System

The proposed system integrates renewable energy, intelligent sensing, and smart communication to provide farmers with a robust and sustainable solution for precision agriculture. The design is segmented into five key functional modules, each contributing to seamless automation and data management in the field as shown in figure 1 [11].

Power Regulation and Battery Charging

The system utilizes a 6V solar panel as its primary energy source. This harvested solar energy is first stepped down using a 5A buck converter to a stable 3.3V, ideal for charging the onboard Lithium Iron Phosphate (LiFePO_4) battery. To ensure safe and efficient charging, a TP5000 charger module is employed. This module intelligently regulates the charging cycle based on the battery's voltage and state, preventing overcharging and enhancing battery longevity. The use of solar power ensures off-grid functionality, making the system suitable for deployment in remote agricultural areas.

Soil Data Collection and Analysis

For real-time soil monitoring, the system integrates various environmental sensors. These include a moisture sensor, an NPK (Nitrogen, Phosphorus, and Potassium) sensor, and a pH sensor. The ESP32 microcontroller acts as the central processor, gathering and interpreting data from each sensor. Since the NPK sensor requires a higher operating voltage, the 3.3V from the battery is boosted to 9V using an XL4009 step-up converter. The processed data helps determine the soil's fertility status, which is critical for optimizing crop yield.

Automated Camera Deployment and Image Capture

To address pest detection and crop health assessment, the ESP32-CAM module is used for visual monitoring. When triggered – either automatically based on predefined parameters or manually via the app – a mechanized rod extends to position the camera above the crops. Once deployed, the ESP32-CAM captures high-resolution images, which can later be analyzed for signs of disease or pest infestation. This automated surveillance significantly decreases the need for human power field inspections.

Data Transmission and Farmer Notifications

All sensor readings, including moisture levels, NPK values, pH status, and camera data, are compiled and transmitted using a GSM module. This module sends an SMS alert directly to the farmer's mobile phone, offering both real-time insights and personalized crop recommendations. To ensure reliable communication between the sensors and the ESP32, particularly over longer distances or in electrically noisy environments, an RS485 communication protocol is employed. This enhances data integrity and system robustness.

User Interaction via Mobile Application

The system offers a user-friendly mobile application built using Kivy (for the frontend interface) and Flask (for the backend API) [12]. Through the app, farmers can remotely access live sensor data, receive tailored crop recommendations based on soil parameters, and even control camera deployment. The app bridges the digital divide, making advanced agricultural technologies accessible to farmers, regardless of their technical background.

Working Flow of the Designed App

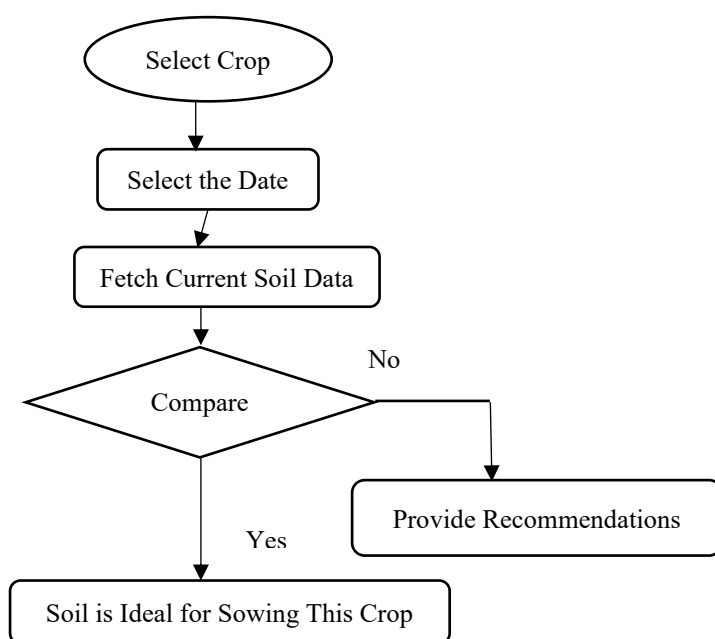


Figure 1. Flow of the App.

RESULTS AND DISCUSSIONS

The IoT based soil monitoring system was thoroughly evaluated under real-world conditions using multiple soil samples collected from active agricultural fields. The system's performance was analyzed based on four critical parameters: sensor accuracy, mobile application functionality, pest detection capabilities, and power reliability. Each component was examined in detail to determine the practicality, consistency, and effectiveness of the system in aiding precision agriculture.

Sensor Performance and Soil Analysis

To evaluate the sensor's accuracy, field samples were collected from three types of cultivation environments: wheat, rice, and sugarcane. The readings obtained from the NPK, and moisture sensors were compared against agronomically accepted nutrient ranges for the respective crops. Additionally, pH values were measured manually using a handheld digital pH meter. The results for wheat and rice fields are presented in Table 1. In the case of wheat, the system detected lack of nitrogen and showed it within the app interface [2, 5]. Fertilizer recommendations were given accordingly. For phosphorus, potassium, and moisture, the readings were within optimal ranges. Similarly, for the rice field, the phosphorus level was below the recommended range, and the system advised appropriate corrective action using phosphate-based fertilizers. Nitrogen and potassium levels, along with the moisture content, were within ideal ranges as shown in figure 2, confirming the field's suitability for paddy cultivation.

Table 1. Analysis and recommendations of different soil parameters by the system.

Parameter	Measured value		Status	Recommendation
Nitrogen (N)	35 mg/kg	40–60 mg/kg	Low	Apply urea or composted manure
Phosphorus (P)	28 mg/kg	20–40 mg/kg	Adequate	No action required
Potassium (K)	42 mg/kg	30–50 mg/kg	Optimal	No action required
Moisture	62%	60–70%	Optimal	Maintain current irrigation levels
pH	6.4 (manual)	6.0–7.0	Neutral	Suitable for wheat and most crops

Mobile Application Functionality

The mobile application, developed using Kivy and connected via Firebase, was tested across multiple Android devices with different screen resolutions and processing capacities. It was observed that the application provided real-time feedback within 1–2 seconds of sensor data reception. The crop recommendation engine effectively interpreted sensor values and suggested relevant fertilizers and soil conditioning techniques. The pest detection page displayed captured images from the ESP32-CAM module without any significant delay. Though SMS-based offline communication was in the prototype phase, Bluetooth connectivity was functional and supported basic sensor control commands.

Pest Detection Analysis

The pest detection module utilized the ESP32-CAM to capture leaf images in areas showing early symptoms of disease. The system performed image enhancement using local contrast analysis and histogram-based techniques to identify infection-prone areas. Although a trained AI model was not implemented at this stage, the analysis still enabled basic detection of fungal infections and discoloration symptoms. A sample output indicated fungal patches on maize and advised the use of organic solutions such as neem oil spray. This preliminary output proves the feasibility of incorporating image-based pest detection in future iterations with machine learning capabilities [13, 14].

System Reliability and Power Performance

The IoT based soil monitoring system was tested under typical farm conditions and exhibited stable performance. Powered by a 6000mAh LiFePO4 battery and a 6W solar panel, the system operated for over 24 hours on a single charge. Data upload and image capture were completed within a few seconds, ensuring real-time responsiveness. Voltage regulation and waterproof casing contributed to its reliability in outdoor environments, making it well-suited for rural deployment [15].

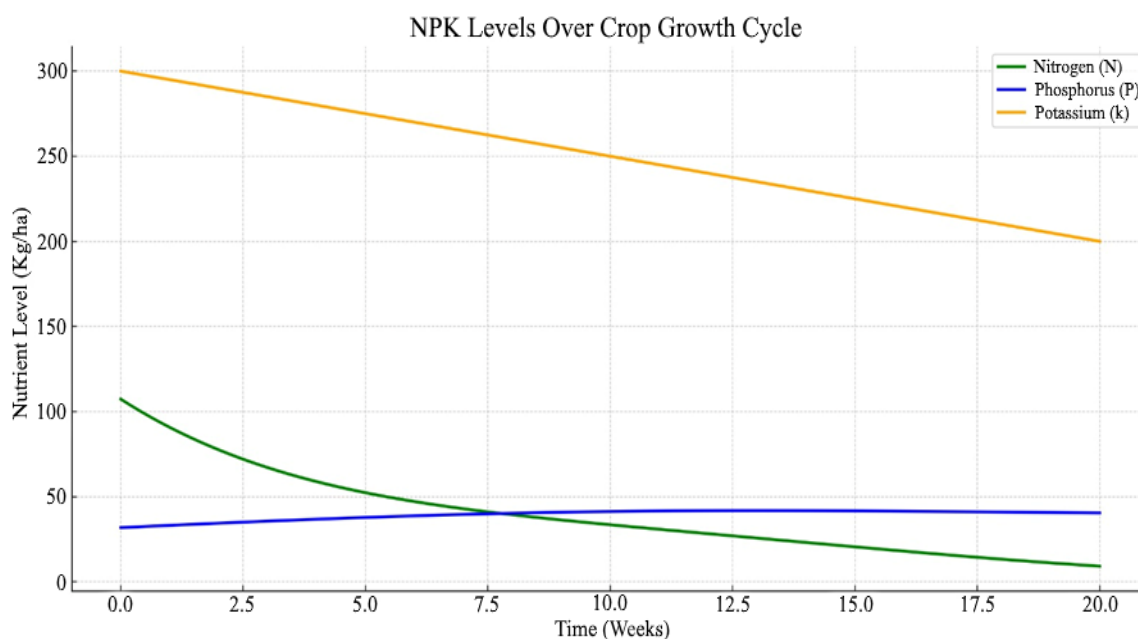


Figure 2. NPK Levels over crop growth.

ADVANTAGES

- *Cost-Effective Implementation:* Utilizes affordable hardware such as the ESP32, RS485 sensors, and a 6W solar panel, keeping the total system cost under ₹6000 – ideal for small and marginal farmers.
- *Real-Time Soil Monitoring:* Enables continuous and on-demand monitoring of soil nitrogen, phosphorus, potassium, moisture, and pH levels, helping in timely decision-making.
- *Personalized Crop Recommendations:* The mobile app analyses sensor data and recommends appropriate crops, fertilizers, and organic treatments.
- *Early Pest Detection:* Captures leaf images and uses contrast-based analysis to detect early signs of fungal or insect attacks.
- *Offline Functionality:* Operates using Bluetooth and SMS modes, ensuring data access even in no-network zones.
- *Environment-Friendly:* Solar powered and supports organic farming practices.
- *Data Storage & Analytics:* Firebase integration allows historical data tracking.
- *Farmer-Friendly Interface:* Kivy-based Android app is intuitive and responsive.
- *Custom Sensor Control:* Each sensor can be controlled individually.
- *Scalability:* System allows for easy expansion with more sensors or AI capabilities [16, 17].

CONCLUSIONS

The IoT based soil monitoring system successfully integrates various sensor technologies to monitor soil health and provide valuable insights for farmers. By combining real-time data from moisture, NPK, and pest detection sensors with advanced data analysis capabilities, the system empowers farmers to make informed decisions regarding soil management and crop cultivation. The mobile application further enhances the accessibility and user-friendliness of the system, offering features such as crop selection, soil health recommendations, and pest detection, all in a seamless interface.

The system's ability to monitor key parameters like soil moisture, nutrient levels, and pest infestations, and to provide actionable insights, presents a significant advancement in precision agriculture. The incorporation of Firebase for cloud storage ensures that data can be accessed and analysed efficiently, further supporting the app's recommendations. This approach promises to reduce crop loss, improve yields, and promote sustainable farming practices.

In conclusion, system demonstrates the potential of technology in transforming agriculture by providing farmers with the tools to optimize crop production, reduce resource wastage, and enhance overall farm productivity. With future enhancements, such as adding more sensor types and expanding the system's reach The IoT based soil monitoring system could revolutionize the way farmers interact with and manage their land, fostering a more sustainable and productive agricultural environment.

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