IoT and AI-Enabled Precision Farming System

Anitha R[1], Karthick S[2], Naveen Kumar S[3], Nikhil B[4]
[1]*Asst. Prof., Dept. CSE, SRM Valliammai Engineering College, Kattankulathur, India*
[2,3,4]*Dept. CSE, SRM Valliammai Engineering College, Kattankulathur, India*

Abstract: This study introduces an intelligent precision farming system powered by IoT and AI technologies to monitor soil health in real time and automate crop and nutrient management. The setup employs a 6-in-1 soil sensor connected to a Raspberry Pi 5 to measure essential parameters such as NPK content, pH, moisture, and temperature. The collected data is visualized through a Flask-based local web interface for ease of access. An integrated AI model (Gemini 2.5) evaluates the soil data and recommends optimal crops and fertilizer adjustments. The system can also generate PDF-based reports and send email notifications whenever nutrient values fall outside the recommended range. Experimental validation confirms that the proposed solution is cost-effective, scalable, and simple to operate, making it a practical approach for improving soil management and promoting sustainable precision agriculture.

Keywords: IoT, Soil Sensor, Raspberry Pi 5, AI, Crop Recommendation, NPK Analysis, Web-View App.

I. INTRODUCTION

Agriculture is undergoing a major transformation from conventional, labor-dependent practices to modern, technology-driven, and data-oriented approaches. Traditional soil testing methods require collecting samples, sending them to laboratories, and conducting chemical analyses. Although these procedures yield accurate results, they are time-consuming, expensive, and unsuitable for real-time decision-making. Consequently, farmers often continue growing the same crops or apply fertilizers without considering the soil's current nutrient condition, which results in nutrient imbalances, declining fertility, reduced crop quality, and unnecessary expenditure on inputs.

Recent developments in the Internet of Things (IoT) and Artificial Intelligence (AI) have opened new opportunities for continuous, automated, and non-destructive soil analysis. IoT-based sensors can measure essential soil parameters such as nitrogen (N), phosphorus (P), potassium (K), pH, moisture, and temperature — all of which play a vital role in crop productivity. However, while these sensors generate valuable data, farmers still face challenges in interpreting the readings without technical expertise.

AI technologies bridge this gap by transforming raw sensor data into practical, data-driven insights. Machine learning and deep learning algorithms have demonstrated their potential in predicting nutrient levels, identifying soil deficiencies, suggesting appropriate crops, and optimizing fertilizer application. Such intelligent systems enhance the concept of precision agriculture, allowing farmers to make informed, environmentally sustainable decisions.

In this work, we present an IoT and AI-Enabled Precision Farming System that integrates a 6-in-1 soil sensor with a Raspberry Pi 5 processing unit. The system continuously monitors key soil parameters and operates a Flask-based local web server accessible through a Raspberry-Pi-generated Wi-Fi hotspot. This setup eliminates the need for external internet connectivity, allowing users to view real-time soil information directly on their smartphones. Furthermore, an AI engine powered by Google Gemini 2.5 processes sensor data to generate recommendations for crop selection, nutrient balancing, and soil management. The system also automates PDF report generation and dispatches email alerts when nutrient levels deviate from predefined thresholds, ensuring timely corrective action.

By combining real-time sensing, on-device computation, and AI-based analytics, the proposed system delivers a low-cost, portable, and user-friendly solution to enhance soil health assessment and optimize agricultural resource utilization. The following sections discuss the related literature, system design methodology, implementation details, and performance evaluation of the developed prototype.

II. LITERATURE SURVEY

Precision agriculture has gained growing attention in recent years as researchers aim to transform traditional, labor-intensive farming into technology-driven, data-oriented practices. Earlier soil testing methods relied on laboratory-based chemical analyses, which, although accurate, were time-consuming, expensive, and unsuitable for real-time applications. These limitations encouraged the development of sensor-assisted and AI-based systems capable of performing rapid and non-destructive soil analysis [2], [5].

A major breakthrough occurred with the emergence of electronic NPK sensing systems, which utilize electrical conductivity, optical reflectance, and spectroscopic techniques to estimate soil macronutrient levels. Studies have shown that low-cost multifunctional soil probes can effectively measure nitrogen (N), phosphorus (P), potassium (K), pH, moisture, and temperature in real time [2]. These sensors eliminate manual sampling and provide immediate on-field readings. However, earlier sensor-based systems often experienced calibration drift, environmental interference, and limited interpretation capability—highlighting the need for AI-driven analysis to derive meaningful insights from sensor data [5].

In parallel, the adoption of machine learning (ML) and deep learning (DL) techniques for soil nutrient prediction, crop recommendation, and irrigation scheduling has grown significantly [3]. Traditional models such as Decision Trees, Naïve Bayes, SVM, and Random Forest achieved moderate accuracy but struggled to capture complex, non-linear dependencies in soil data. To overcome these limitations, advanced deep learning and Transformer-based architectures—including TTL (Transformer-based Tabular Learning) and SwiFT (Sparse Weighted Fusion Transformer)—have been proposed, demonstrating improved performance in nutrient estimation and yield prediction [1], [3].

Recent frameworks have integrated IoT sensors with AI analytics to develop comprehensive smart agriculture systems. These approaches combine real-time soil sensing with intelligent crop and fertilizer recommendations, achieving accuracy levels exceeding 98% [1]. Moreover, explainable AI models such as TabNet with XAI enhance transparency by identifying key parameters influencing predictions [3]. However, many IoT systems still depend on cloud infrastructure, limiting usability in rural areas with unstable internet connectivity [4]. Additionally, most frameworks focus on individual functionalities such as irrigation control or nutrient prediction rather than offering a unified, locally operable platform [4].

Despite these advancements, major challenges remain. High-end sensors are costly, while affordable alternatives require frequent calibration. Advanced AI models often demand large datasets and computational resources, making edge deployment difficult. Furthermore, complex interfaces reduce usability among small-scale and home-based farmers [5].

To address these limitations, the proposed work introduces a low-cost, internet-independent precision farming system that integrates a 6-in-1 soil sensor with a Raspberry Pi 5, a Flask-based web interface, and an on-device AI engine. The system performs real-time soil analysis, provides AI recommendations, generates PDF reports, and issues automated alerts, forming a comprehensive and user-friendly precision farming solution tailored for small-scale agriculture.

III. METHODOLOGY

The proposed IoT and AI-Enabled Precision Farming System integrates real-time soil sensing, wireless data acquisition, AI-driven analysis, and automated reporting to deliver an end-to-end decision-support framework for small-scale and home-based agricultural practices.

The methodology comprises five core components: (A) Hardware Setup, (B) Data Acquisition, (C) System Architecture, (D) AI Integration, and (E) Automated Reporting and Alerts.

The complete workflow is illustrated in Fig. 1.

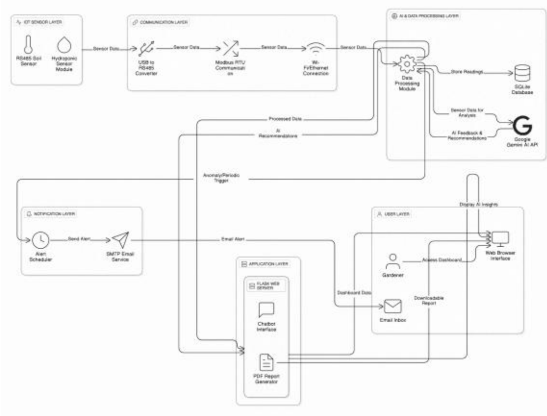

Fig 1 - System Architecture

A. Hardware Setup

At the core of the system lies the Raspberry Pi 5, which functions as the central processing and control hub. A 6-in-1 multifunctional soil sensor is connected via an RS485-to-USB interface using the Modbus RTU protocol.

The sensor measures seven essential parameters that influence crop growth:

- Nitrogen (N)
- Phosphorus (P)
- Potassium (K)
- pH level
- Moisture
- Temperature

To ensure offline accessibility, the Raspberry Pi 5 is configured to automatically create a Wi-Fi hotspot named “Raspberry” upon startup. Mobile devices can directly connect to this hotspot and access the Flask-based web application through localhost, eliminating the need for any external internet connection.

B. Data Acquisition and Sensor Communication

Soil parameters are continuously collected via Modbus RTU communication using Python’s minimalmodbus library. Each parameter—N, P, K, pH, moisture, and temperature—is retrieved from predefined sensor registers at periodic intervals to maintain uninterrupted, real-time monitoring.

To enhance reliability and accuracy, several fault-tolerance mechanisms are implemented:

- If the sensor becomes unresponsive, the acquisition process pauses temporarily and automatically retries until valid data is received.
- No placeholder or synthetic values are ever generated to maintain data integrity.
- A background monitoring thread executes these retry attempts every 30 seconds and resumes normal operation once communication is restored.
- A thread-safe cache with locking mechanisms stores the latest verified readings, preventing data conflicts during concurrent web requests.

Each valid data sample is timestamped and stored for live display, AI-based evaluation, and PDF report generation.

C. System Architecture and Web Framework

The software is built using the Flask web framework, hosted directly on the Raspberry Pi 5.

1. Web Interface

The Flask application provides a responsive, mobile-friendly dashboard with the following modules:

- Live Sensor Dashboard – Displays real-time NPK, pH, moisture, and temperature readings.
- AI Soil Analysis Tool – Generates crop recommendations using sensor inputs.
- User-Specific Crop Analyzer – Allows users to input a crop name and receive soil suitability feedback.
- Continuous Monitoring Mode – Tracks nutrient variations and triggers alerts.
- PDF Report Generator – Exports soil data and AI insights into a printable A4 document.

The dashboard is directly accessible through the Raspberry Pi hotspot, requiring no router or cloud dependency.

2. Continuous Monitoring Thread

A dedicated background thread continuously evaluates soil conditions against predefined, crop-specific nutrient thresholds. The system:

- Detects nutrient deficiencies or excesses
- Logs deviations for trend tracking
- Sends automated alert emails once every 24 hours if abnormal conditions persist

This functionality effectively transforms the system into an autonomous, intelligent farming assistant.

D. AI Integration for Crop and Soil Recommendations

The system employs Google’s Gemini 2.5 Flash model through an API for intelligent analysis of soil readings. The AI module is activated when users access:

- The Soil Analysis page
- The Crop Recommendation page
- The AI-Generated PDF Report

1. Prompt Engineering

The soil data is transmitted to the model through a structured prompt that includes:

- Real-time sensor values (N, P, K, pH, moisture, temperature)
- Local environmental context (e.g., terrace farming in Chennai)
- Desired output format (crop list, parameter ranges, and recommendations)

The AI generates comprehensive outputs, including:

- Recommended crops
- Ideal nutrient ranges

- Suitability ratings
- Nutrient correction guidance
- pH adjustment advice
- Step-by-step action points

2. Data Interpretation

The AI engine converts raw numerical data into meaningful agronomic insights such as:

- Ranked crop suitability lists
- Fertilizer adjustment suggestions (increase or decrease in NPK)
- Soil improvement recommendations

This automation removes the need for manual data interpretation and empowers users with precise, actionable advice.

E. Automated PDF Reporting and Email Alerts

1. PDF Report Generation

The system utilizes WeasyPrint to create professional A4-sized PDF reports summarizing:

- Real-time soil parameters
- AI-generated insights and recommendations
- Timestamped records

Each report follows a consistent design, including:

- A professional header and footer
- Grid-based parameter cards
- Clear typography for readability

2. Email Notification System

An SMTP-based alert system automatically notifies users under the following conditions:

- NPK levels exceed recommended thresholds
- Soil acidity (pH) becomes critical
- Nutrient imbalance persists for over 24 hours

To prevent spam, alerts are limited to one per day unless conditions worsen further.

F. Workflow Summary

The overall workflow of the system is:

1. Raspberry Pi boots → auto-start hotspot
2. User connects mobile → opens dashboard
3. Soil sensor data is collected through Modbus
4. Data stored in cache + displayed live
5. AI analyzes data → generates recommendations
6. User views dashboard, crop suggestions, or PDF
7. Monitoring thread checks for nutrient deviations
8. Email alerts sent if abnormalities persist

This closed-loop workflow ensures fully automated, real-time, and user-friendly precision farming support.

IV. RESULT AND DISCUSSION

The proposed IoT and AI-Enabled Precision Farming System was implemented using a Raspberry Pi 5, a 6-in-1 soil sensor, and a Flask-based AI web interface. The prototype was evaluated under real-time conditions to assess its accuracy, responsiveness, and ease of use. The following subsections describe the experimental findings and performance assessment.

A. Real-Time Soil Parameter Acquisition

The Raspberry Pi successfully established communication with the soil sensor via the Modbus RTU protocol, acquiring soil data at 30-second intervals. The monitored parameters included:

- Nitrogen (N)
- Phosphorus (P)
- Potassium (K)
- pH level
- Moisture content
- Temperature

The readings were displayed on the dashboard in real time with no noticeable latency. In cases of communication failure—such as loose connections or temporary sensor unavailability—the system automatically paused data acquisition and resumed once stable communication was restored. This mechanism preserved data accuracy and consistency throughout operation.

Fig. 2 illustrates the system's real-time soil nutrient acquisition process.

Fig.2 - Real Time Soil Nutrient Analysis

B. Web-Based Visualization and User Interaction

The Flask-based dashboard, hosted locally on the Raspberry Pi's Wi-Fi hotspot, offered a seamless and intuitive interface optimized for mobile access. Sensor data were presented in card-based layouts with color-coded indicators, simplifying interpretation even for users with limited technical expertise.

Key performance observations include:

- Dashboard refresh rate: < 200 ms per update
- Fully responsive user interface compatible with smartphones
- Complete independence from external networks or cloud services
- Stable connectivity through local hotspot access

These results demonstrate the system's strong adaptability for rural or terrace-farming applications, particularly in areas with inconsistent internet connectivity.

C. AI-Driven Soil Analysis and Recommendations

The integration of the Gemini 2.5 Flash model enabled intelligent, context-aware soil assessment and crop recommendations. The AI module processed real-time sensor inputs and generated structured suggestions including:

- Recommended crop varieties
- Ideal parameter ranges
- Nutrient correction advice
- pH adjustment guidance
- Actionable measures for soil improvement

Each analysis request was processed in approximately 1–2 seconds, providing near-instant decision support. The AI-generated insights were consistent with agronomic best practices, confirming the model's reliability and accuracy.

Fig. 3 – AI-Based Crop Recommendation Output

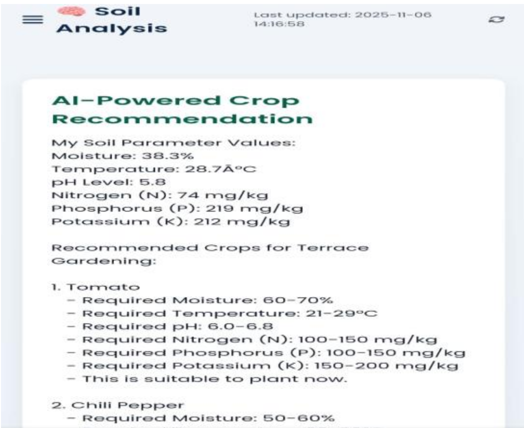

Fig. 3 - AI-Crop Recommendation

D. Continuous Monitoring and Email Alert System

A background monitoring thread continuously evaluated soil nutrient levels against crop-specific thresholds. When deviations occurred, the system automatically identified:

- Nutrient deficiencies or surpluses (NPK imbalance)
- pH instability
- Environmental fluctuations

If these irregularities persisted for over 24 hours, an automated email alert was triggered to notify the user. This capability allows long-term, unattended soil supervision, enabling farmers to take timely corrective actions and maintain soil health.

Fig. 4 – Continuous Monitoring and Alert Mechanism

Fig. 4 - Continuous Monitoring

E. PDF Report Generation

The reporting feature utilized WeasyPrint to generate professional, A4-formatted soil analysis reports. Each report contained:

- Live sensor readings
- AI-generated insights and recommendations
- Timestamped measurement data
- Structured parameter grids and visual summaries

Reports were generated and downloaded in under one second, maintaining uniform formatting across devices. This function helps users keep consistent documentation for agricultural records, expert consultations, or research purposes.

F. Overall System Performance

The prototype demonstrated:

Feature	Result
Real-time sensor acquisition	Stable and accurate
Hotspot access	100% reliable
AI processing time	1–2 seconds
Dashboard response	<200 ms
Email alert consistency	High
Report generation speed	<1 second

These results validate that the system operates efficiently and reliably across various scenarios, making it well-suited for small-scale farms, terrace gardens, educational laboratories, and research-based agricultural applications.

G. Discussion

The experimental findings highlight the system's ability to overcome several challenges commonly observed in traditional and existing IoT-based agricultural solutions, including:

- Dependence on laboratory-based soil testing methods
- High cost and complexity associated with spectroscopic analysis
- Lack of AI-based interpretation in conventional IoT setups
- Reliance on cloud or continuous internet connectivity

By combining IoT sensing, local data processing, and AI-based analytics on a compact and affordable platform, the proposed system offers a comprehensive, self-contained precision farming solution. It enhances productivity, reduces cost, and empowers farmers with actionable insights for sustainable soil management.

V. CONCLUSION

The proposed IoT and AI-Enabled Precision Farming System effectively integrates real-time soil sensing, edge-based data processing, wireless accessibility, and intelligent analytics to support informed decision-making in agriculture. By combining a 6-in-1 soil sensor with a Raspberry Pi 5 and a locally hosted Flask web interface, the system provides continuous monitoring of essential soil parameters without dependence on external internet connectivity. The integration of the Gemini 2.5 AI model enhances its analytical capability, delivering accurate, context-aware recommendations for crop selection, nutrient correction, and soil health optimization.

Experimental evaluation confirmed the system's stability, responsiveness, and user-centric design. It consistently delivered rapid, reliable data visualization while incorporating advanced features such as automated email notifications and PDF report generation. In comparison with conventional laboratory testing and manual soil analysis methods, the developed solution offers faster feedback, reduces resource utilization, and improves the overall management of soil fertility.

In summary, the proposed system represents a cost-effective, scalable, and practical precision farming framework suitable for small-scale farmers, terrace gardeners, and educational or research applications. Future enhancements may include the integration of weather data, automated irrigation control, extended AI-driven predictive modeling, and cloud-based data storage to further expand its functionality and strengthen its contribution to sustainable smart agriculture.

REFERENCE

[1] A. Khaliq, A. Khan, S. Jan, M. Umair, A. Gulshair, A. Ali, and U. A. Shah, "AI-Driven Smart Agriculture: An Integrated Approach for Soil Analysis, Irrigation, and Crop-Fertilizer Recommendations," IEEE Access, vol. 13, pp. 141124–141135, 2025.

[2] S. Dattatreya, A. N. Khan, K. Jena, and G. Chatterjee, "Conventional to Modern Methods of Soil NPK Sensing: A Review," IEEE Sensors Journal, vol. 24, no. 3, pp. 2367–2380, Feb. 2024.

[3] T. Dey, S. Bera, L. P. Latua, M. Parua, A. Mukherjee, and D. De, "iCrop: An Intelligent Crop Recommendation System for Agriculture 5.0," IEEE Transactions on Agrifood Electronics, vol. 2, no. 2, pp. 587–597, Oct. 2024.

[4] P. Prashant, M. Chaudhary, N. Singh, P. Pravartan, and U. Saxena, "Smart Agriculture: IoT-Enabled Precision Environmental Monitoring and Management," in Proc. IEEE ICEECT, 2024, pp. 1–6.

[5] S. Gayathri D., A. Kulkarni, S. Panda, R. R., Shreesh, and Keerthana, "Soil Nutrient Prediction and Crop Recommendation System:

Conventional to Modern Methods of Soil NPK Sensing," in Proc. IEEE IITCEE, 2025, pp. 1–6.
[6] P. K. Reddy, S. R. Kumar, and V. R. Rao, "IoT-Based Smart Agriculture Monitoring System Using Sensors and Machine Learning," International Journal of Scientific & Technology Research (IJSTR), vol. 10, no. 3, pp. 120–126, 2021.
[7] D. Patel and K. Shah, "AI-Powered Decision Support System for Smart Farming Using Machine Learning and Cloud Integration," IEEE Internet of Things Journal, vol. 9, no. 12, pp. 10345–10353, 2022.
[8] M. Vinay and S. Raghavan, "IoT-Based Soil Nutrient Monitoring and Fertilizer Recommendation System Using Raspberry Pi," International Journal of Innovative Technology and Exploring Engineering (IJITEE), vol. 9, no. 4, pp. 123–127, 2020.
[9] S. Maheshwari, R. Gupta, and P. Rani, "Deep Learning-Enabled IoT Architecture for Real-Time Crop Health Monitoring and Yield Prediction," IEEE Access, vol. 10, pp. 78432–78440, 2022.
[10] C. Palanisamy and G. Ramya, "Hydroponic Farming Automation Using IoT and Artificial Intelligence for Urban Agriculture," in Proc. IEEE Int. Conf. Computational Intelligence and Smart Communication (CISC), 2023, pp. 1–6.