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Smart Soil Nutrient Detection and Crop Recommendation System Using Sensors and IoT

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Abstract - Agriculture is one of the most important sectors for food production and economic growth. However, many farmers still face problems in identifying soil nutrients and selecting suitable crops for cultivation. Traditional soil testing methods are expensive, time-consuming, and not easily accessible for small-scale farmers. Due to lack of proper soil analysis, farmers often use excessive fertilizers and grow crops that are not suitable for their land, resulting in lower productivity and reduced profit.

This research presents a Smart Soil Nutrient Detection and Crop Recommendation System using sensors and IoT technology. The proposed system uses chemical soil testing methods along with sensors to detect soil nutrients such as Nitrogen (N), Phosphorus (P), Potassium (K), pH level, soil moisture, and temperature. The collected data is processed using a microcontroller and transferred to a cloud-based dashboard through IoT communication.

Keywords: Smart Agriculture, IoT, Soil Nutrient Detection, Crop Recommendation ,Precision Farming, ESP32 Sensors, Artificial Intelligence

1. Introduction

In traditional farming practices, many farmers rely on personal experience and manual observation to determine soil quality and crop selection. However, these methods are often inaccurate and may not provide complete information about the nutrient condition of the soil. Farmers usually do not know the exact quantity of essential nutrients such as Nitrogen (N), Phosphorus (P), Potassium (K), soil moisture, pH level, and temperature conditions present in their farmland. Due to the lack of proper soil analysis, unsuitable crops are cultivated, fertilizers are excessively used, and farming productivity is reduced.

Traditional laboratory-based soil testing methods are available to analyze soil nutrients, but they involve several limitations. Soil samples need to be collected manually and sent to testing laboratories for examination. This process is expensive, time-consuming, and difficult for small-scale farmers, especially those living in rural areas where laboratory facilities may not be easily accessible. Delays in receiving test results can also affect farming decisions and crop planning.

Artificial intelligence and machine learning techniques further improve the effectiveness of smart agriculture systems by analyzing collected data and generating intelligent recommendations. Machine learning algorithms can identify patterns in soil and environmental conditions and predict the most suitable crops for cultivation. These technologies help farmers make scientific and data-driven decisions instead of depending only on traditional assumptions and manual observation.

The proposed Smart Soil Nutrient Detection and Crop Recommendation System using Sensors and IoT is designed to provide an automated, low-cost, and intelligent farming solution. The system combines chemical soil testing methods, sensor technology, IoT communication, and AI-based crop recommendation techniques into a single platform. In this system, soil samples are tested using chemicals that produce color changes based on nutrient levels. A TCS3200 color sensor detects these color variations, while other sensors measure soil moisture, pH, temperature, and NPK values.

The collected data is processed using a microcontroller such as ESP32 or Arduino and transmitted to a cloud-based dashboard through Wi-Fi or GSM communication. The system then analyzes the data using intelligent recommendation logic and suggests suitable crops that can grow effectively under the detected soil conditions. It can also provide fertilizer recommendations and profit-oriented crop suggestions to support better agricultural planning.

The proposed system offers several advantages over traditional farming methods. It reduces dependency on laboratory testing, provides faster soil analysis, minimizes fertilizer wastage, improves crop productivity, and supports precision farming practices. The system is designed to be affordable, portable, and easy to use, making it suitable for both small-scale and large-scale farmers.

The primary objectives of the CalmConnect are as follows:

- To develop a smart and automated soil testing system using IoT technology.
- To detect important soil nutrients such as Nitrogen (N), Phosphorus (P), and Potassium (K).
- To measure soil parameters including pH level, moisture, and temperature using sensors.
- To reduce dependency on traditional laboratory-based soil testing methods.
- To provide real-time monitoring of soil conditions through IoT communication.

The remainder of this paper is organized as follows: Section II presents a review of related work in ride-sharing and transportation systems. Section III describes the system architecture, methodology, and implementation details. Section IV discusses performance evaluation and results. Section V highlights limitations and future enhancements. Finally, Section VI concludes the paper.

2. Literature Review

a. IoT in Smart Agriculture

The Internet of Things (IoT) has become one of the most important technologies in modern agriculture. IoT allows different sensors and devices to collect real-time information from agricultural fields and transfer the data through internet-based communication systems. Smart agriculture systems use IoT devices to monitor environmental and soil conditions continuously, helping farmers make accurate and timely decisions..

Several researchers have developed IoT-based agricultural monitoring systems that use sensors to measure parameters such as soil moisture, temperature, humidity, and pH level. These systems help farmers automate irrigation, monitor crop health, and improve farming productivity. IoT-based monitoring also reduces human effort and minimizes water and fertilizer wastage.

They often rely on predefined responses or simple models, which makes it difficult for them to understand complex language or context. As a result, the interaction may feel repetitive or less personalized. Additionally, most chatbot systems focus only on conversation and do not include features like community support or activity-based engagement.

Although IoT-based systems provide effective monitoring solutions, many existing models mainly focus on environmental monitoring and do not provide detailed soil nutrient analysis or intelligent crop recommendation features. This creates the need for more advanced systems that combine IoT with nutrient detection and AI-based recommendations..

2.2 Soil Nutrient Detection Systems

Soil nutrient analysis is one of the most important processes in agriculture because soil fertility directly affects crop growth and productivity. Nutrients such as Nitrogen (N), Phosphorus (P), and Potassium (K) play a major role in plant development. Deficiency or excess of these nutrients can reduce crop yield and affect soil health.

Traditional soil testing methods involve collecting soil samples and sending them to laboratories for analysis. While these methods provide accurate results, they are time-consuming, expensive, and not easily accessible for small-scale farmers. Due to these limitations, researchers have developed sensor-based soil nutrient detection systems to simplify soil analysis..

Researchers have concluded that sensor-based soil analysis systems can help farmers better understand soil conditions and reduce fertilizer misuse. However, many existing systems are limited to nutrient detection only and do not provide intelligent crop recommendations based on soil conditions.

2.3 Machine Learning in Crop Recommendation

Among various algorithms, Random Forest is commonly preferred because it provides high prediction accuracy and handles large datasets effectively. Decision Tree algorithms are also widely used because they are simple to understand and easy to implement. KNN algorithms help classify crops based on similarities between soil conditions and previous agricultural data.

Machine learning has become widely used in agriculture for predicting crop yield, identifying diseases, and recommending suitable crops. Machine learning algorithms analyze large amounts of agricultural data and identify patterns that can help farmers make scientific decisions.

Several researchers have developed crop recommendation systems using machine learning algorithms such as Decision Tree, Random Forest, Support Vector Machine (SVM), and K-Nearest Neighbor (KNN). These systems use input parameters such as NPK values, temperature, humidity, rainfall, and pH level to predict suitable crops for cultivation.

2.4 Sensor Technologies Used in Smart Farming

Sensors play an important role in smart agriculture systems because they help collect real-time data from the environment and soil.

Researchers have widely used soil moisture sensors to measure water content in soil and improve irrigation management. pH sensors are used to determine soil acidity and alkalinity, which directly affect nutrient absorption by plants. Temperature and humidity sensors such as DHT11 and DHT22 are commonly used for environmental monitoring..

NPK sensors are used to measure essential soil nutrients including Nitrogen, Phosphorus, and Potassium. In some advanced systems, color sensors such as the TCS3200 are used to analyze chemical color reactions for nutrient detection.

2.5 Cloud Computing and IoT Communication in Agriculture

Cloud computing and IoT communication technologies are widely used in modern smart farming systems to store, manage, and analyze agricultural data remotely. IoT devices collect data from sensors and send the information to cloud servers using communication technologies such as Wi-Fi, GSM, Bluetooth, Zigbee, and MQTT protocols.

Researchers have developed cloud-based agricultural monitoring systems that allow farmers to access real-time soil and environmental data through mobile applications and web dashboards. Platforms such as ThingSpeak, Firebase, and Blynk are commonly used for cloud storage and visualization in IoT-based farming projects.

Cloud computing enables large-scale data storage and remote monitoring, making it easier for farmers to manage agricultural activities from different locations. Real-time notifications and analytics also help farmers take preventive actions during unfavorable farming conditions.

Studies show that cloud-based smart agriculture systems improve efficiency, support data-driven farming decisions, and reduce manual monitoring efforts. However, internet connectivity issues in rural areas remain one of the major challenges for cloud-based agricultural systems.

2.6 Research Gap and Need for Proposed System

From the literature survey, it is observed that several researchers have developed systems related to IoT-based monitoring, soil analysis, and crop recommendation. However, many existing systems focus only on individual features such as moisture monitoring, irrigation automation, or environmental analysis.

Some systems provide soil nutrient detection but do not include intelligent crop recommendation features. Other systems use machine learning algorithms for crop prediction but rely mainly on historical datasets instead of real-time sensor data. In many cases, the systems are expensive, difficult to maintain, or not suitable for small-scale farmers.

3. Methodology

3.1 Soil Sample Collection and Preparation

The first step in the proposed system is the collection of soil samples from agricultural land. Proper soil sampling is important because the accuracy of nutrient analysis and crop recommendation mainly depends on the quality of the collected sample. Farmers collect small quantities of soil from different areas of the field to ensure that the sample represents the actual condition of the farmland.

After collection, the soil samples are cleaned to remove unwanted particles such as stones, roots, and dry leaves. The collected soil is then dried and prepared for testing. For nutrient analysis, the soil sample is mixed with specific chemical solutions that react with nutrients such as Nitrogen (N), Phosphorus (P), and Potassium (K). Depending on the nutrient concentration present in the soil, the chemical solution changes color.

This color-based chemical testing method helps identify nutrient levels in an affordable and practical manner. The prepared soil sample is then placed near the sensing unit for further analysis through sensors and microcontrollers.

The proposed system uses chemical testing methods to identify soil nutrients such as Nitrogen (N), Phosphorus (P), and Potassium (K). In this process, the soil sample is mixed with specific chemical reagents designed for nutrient testing. When these chemicals react with the nutrients present in the soil, visible color changes occur. Different colors or color intensities indicate different nutrient concentrations in the soil.

The color reaction process is an important part of the system because it allows nutrient analysis using low-cost sensor technology instead of expensive laboratory equipment. The generated color changes are later detected by the TCS3200 color sensor, which converts the color intensity into digital values for analysis.

Once the soil is cleaned and dried, it is crushed gently to remove lumps and make the texture uniform. A fine and uniform soil sample allows better mixing with chemical solutions and improves the effectiveness of nutrient testing. The prepared soil is then transferred into a testing container or sample holder for further analysis.

3.2 Sensor-Based Soil Parameter Detection

After preparing the soil sample, different sensors are used to measure important soil and environmental parameters. The proposed system uses multiple sensors to collect real-time information about soil fertility and environmental conditions

The NPK sensor is used to detect the concentration of essential nutrients such as Nitrogen, Phosphorus, and Potassium present in the soil. These nutrients are very important for healthy plant growth and agricultural productivity.

3.3 Microcontroller Processing and IoT Communication

The collected sensor data is processed using a microcontroller such as ESP32 or Arduino UNO. The microcontroller acts as the main processing unit of the system and controls communication between sensors, cloud platforms, and the dashboard.

The ESP32 microcontroller is preferred because it supports built-in Wi-Fi communication, faster processing, and efficient IoT connectivity. Sensor values collected from different sensors are converted into digital data and processed by the controller.

Cloud platforms such as ThingSpeak, Firebase, or Blynk can be used to store and monitor sensor data remotely. This allows farmers to access soil reports and monitoring information from mobile devices or computers.

The IoT communication system enables real-time monitoring of soil conditions and improves accessibility for farmers. It also helps maintain digital records of soil reports for future agricultural planning and analysis.

3.4 Data Analysis and Crop Recommendation

3.4.1 Data Collection and Input Parameters

The first stage of the data analysis process involves collecting sensor data from the agricultural field. Different sensors continuously monitor soil nutrients and environmental conditions and send the collected information to the microcontroller.

These parameters are very important because different crops require different nutrient concentrations and environmental conditions for healthy growth. For example, rice requires high moisture levels, while crops such as cotton can tolerate drier conditions.

3.4.2 Data Preprocessing and Validation

Before applying recommendation algorithms, the collected sensor data is preprocessed and validated to improve accuracy and reliability. Raw sensor readings may sometimes contain noise, missing values, or inconsistent data due to environmental interference or sensor limitations.

The preprocessing stage includes:

- Removal of incorrect or duplicate readings
- Handling missing values
- Normalization of sensor values
- Conversion of analog data into usable digital forma

3.4.3 Rule-Based Crop Recommendation

The proposed system initially uses a rule-based recommendation mechanism for basic crop prediction. In this method, predefined agricultural rules are used to identify suitable crops based on soil conditions.

The rules are designed using agricultural knowledge and farming practices. Different crops require specific nutrient levels, pH ranges, moisture content, and temperature conditions for proper growth.

3.4.4 Machine Learning-Based Crop Recommendation

To improve prediction accuracy and intelligent decision-making, the proposed system uses machine learning algorithms for crop recommendation. Machine learning models analyze historical agricultural datasets and identify patterns between soil conditions and crop productivity..

Among these algorithms, Random Forest is commonly preferred because of its high accuracy and ability to handle multiple agricultural parameters efficiently.

3.4.5 Fertilizer Recommendation and Result Generation

After crop prediction, the system generates fertilizer recommendations and final output reports based on nutrient deficiencies detected in the soil.

If the system identifies low nutrient levels, it suggests suitable fertilizers required to improve soil fertility. For example:

- Low Nitrogen → Nitrogen-rich fertilizers
- Low Potassium → Potash fertilizers
- Low Phosphorus → Phosphate fertilizers

3.5 Dashboard Visualization and Report Generation

The development process follows an Agile methodology with iterative improvements.

The final stage of the methodology involves displaying the analyzed data and crop recommendations on a digital dashboard. The dashboard acts as the user interface between the system and the farmer.

The dashboard provides real-time visualization of:

- Soil nutrient levels
- Moisture content
- Temperature and humidity
- pH values
- Crop recommendations
- Fertilizer suggestions

The dashboard can be developed using technologies such as:

- HTML
- CSS
- JavaScript
- Flask
- Node.js

4. Results and Analysis

4.1 Soil Nutrient Detection Results

The proposed Smart Soil Nutrient Detection and Crop Recommendation System successfully detected and analyzed important soil nutrients and environmental parameters using multiple sensors and chemical testing methods. During system testing, different soil samples were collected from agricultural land and analyzed using sensors such as the NPK sensor, pH sensor, soil moisture sensor, temperature sensor, and TCS3200 color sensor.

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The chemical testing process produced visible color changes depending on the concentration of nutrients present in the soil. These color variations were accurately detected by the TCS3200 color sensor, which converted the RGB color intensity into digital values for further analysis. The ESP32 microcontroller processed all sensor readings and transmitted the collected data to the dashboard for real-time monitoring and analysis.

The system successfully measured important soil parameters including Nitrogen (N), Phosphorus (P), Potassium (K), pH level, soil moisture, temperature, and humidity. Based on the sensor readings, the system identified whether nutrient levels were high, medium, or low. For example, soil samples containing higher nitrogen concentration produced darker color reactions during chemical testing, while samples with lower nutrient concentration produced lighter color intensity. Similarly, low pH values indicated acidic soil conditions, while higher moisture readings represented water-rich soil suitable for crops requiring high irrigation levels.

4.2 IoT Monitoring and Dashboard Analysis

The IoT monitoring and dashboard module of the proposed Smart Soil Nutrient Detection and Crop Recommendation System successfully enabled real-time monitoring, storage, and visualization of soil and environmental data. After collecting sensor readings from the agricultural field, the ESP32 microcontroller processed the data and transmitted it to the cloud-based dashboard using IoT communication technologies such as Wi-Fi or GSM. The dashboard acted as a centralized platform where farmers could easily access soil analysis reports, nutrient levels, crop recommendations, and fertilizer suggestions.

The dashboard interface was designed to provide a user-friendly experience for farmers, even for those with limited technical knowledge. The collected sensor data was displayed using charts, tables, graphs, and status indicators, making it easier to understand the current soil condition and environmental status. Real-time updates allowed farmers to monitor changes in soil fertility and moisture conditions instantly without requiring manual observation or repeated laboratory testing. The dashboard also provided visual representation of nutrient levels, helping farmers identify nutrient deficiencies and make better decisions regarding fertilizer usage and crop selection.

The performance of the IoT monitoring system was found to be efficient and reliable during testing. Sensor data was transferred quickly with minimal delay, and the dashboard generated accurate visual reports for analysis.

4.3 Crop Recommendation Analysis

The crop recommendation module of the proposed Smart Soil Nutrient Detection and Crop Recommendation System successfully analyzed soil and environmental conditions and generated suitable crop suggestions based on real-time sensor data. The system used both rule-based logic and machine learning algorithms to identify crops that could grow effectively under the detected soil conditions. Important parameters such as Nitrogen (N), Phosphorus (P), Potassium (K), pH level, soil moisture, temperature, and humidity were considered during the recommendation process. These parameters play a significant role in determining crop suitability because different crops require different nutrient concentrations and environmental conditions for healthy growth and maximum productivity.

The recommendation system compared the collected sensor values with predefined agricultural rules and trained machine learning models to predict appropriate crops

4.4 Overall System Performance and Analysis

The IoT communication module enabled smooth and real-time transfer of sensor data using Wi-Fi or GSM connectivity. Farmers could monitor soil conditions remotely through the dashboard interface, which improved accessibility and reduced the need for manual observation.

The dashboard displayed nutrient levels, environmental conditions, crop suggestions, and fertilizer recommendations in an easy-to-understand format using graphs, charts, and visual indicators. This helped farmers quickly understand the condition of their farmland and make informed agricultural decisions. The cloud-based monitoring system also allowed digital storage of soil reports, making it easier to maintain historical records and track soil fertility changes over time.

5.1 Interpretation of Findings

The results obtained from the proposed Smart Soil Nutrient Detection and Crop Recommendation System indicate that the integration of IoT technology, sensors, and intelligent recommendation techniques can effectively improve modern agricultural practices.

The system successfully monitored soil and environmental conditions in real time and provided meaningful analysis related to soil fertility and crop suitability. The observed sensor readings and dashboard reports demonstrated that the proposed solution can assist farmers in making more accurate and scientific farming decisions.

The soil nutrient detection process showed that the combination of chemical testing methods and sensor-based analysis can provide reliable information about essential nutrients such as Nitrogen (N), Phosphorus (P), Potassium (K), soil pH, moisture, and temperature.

The detected values helped identify nutrient deficiencies and overall soil health conditions. This indicates that low-cost sensor technology can serve as an effective alternative to traditional laboratory-based soil testing methods, especially for small-scale and rural farmers.

5.2 Comparison with Prior Work

The proposed Smart Soil Nutrient Detection and Crop Recommendation System was compared with previously developed smart agriculture systems to evaluate its effectiveness, functionality, and innovation.

Many earlier research works focused mainly on individual agricultural features such as soil moisture monitoring, irrigation control, environmental sensing, or crop prediction separately. However, the proposed system integrates multiple technologies including chemical soil testing, color sensor analysis, IoT communication, cloud monitoring, and intelligent crop recommendation into a single smart agriculture platform.

5.3 Limitations

Although the proposed Smart Soil Nutrient Detection and Crop Recommendation System provides several advantages for modern agriculture, there are certain limitations associated with the system. These limitations may affect the accuracy, efficiency, and practical implementation of the project under different environmental and operational conditions.

One of the major limitations of the system is sensor accuracy and calibration. Sensors such as NPK sensors, pH sensors, moisture sensors, and color sensors may produce inaccurate readings if they are not calibrated properly. Environmental conditions such as temperature changes, dust, humidity, and improper handling can also affect sensor performance.

Regular calibration and maintenance are necessary to ensure accurate soil analysis results.

The proposed system also depends on chemical testing solutions for nutrient detection. Over time, chemical reagents may lose effectiveness or require replacement. Improper chemical handling or incorrect mixing of soil samples may affect the color reaction process and reduce the accuracy of nutrient analysis. Therefore, proper maintenance and careful usage of chemical solutions are important for reliable operation.

5.4 Future Directions

The proposed Smart Soil Nutrient Detection and Crop Recommendation System provides a strong foundation for smart agriculture and precision farming. Although the current system successfully performs soil analysis, IoT monitoring, and intelligent crop recommendation, several advanced features and improvements can be added in the future to increase the efficiency, accuracy, and scalability of the system.

One of the major future directions of the project is the integration of advanced artificial intelligence and deep learning techniques for more accurate crop prediction and agricultural analysis.

Payment Integration

Incorporate secure payment gateways (e.g., Stripe, Razor pay) to enable seamless digital transactions and fare management.

Advanced AI

Implement of advance ai for chatbot of the website by which the accessing of general information would be easier.

One of the major future directions of the project is the integration of advanced artificial intelligence and deep learning techniques for more accurate crop prediction and agricultural analysis.

Computer Vision technology can also be integrated into the system for crop disease detection and plant health monitoring. Cameras connected to AI models can capture images of crop leaves, stems, and fruits, and identify diseases, nutrient deficiencies, or pest infections automatically. CNN-based image classification models can detect diseases at an early stage and help farmers take preventive actions before crop damage becomes severe.

6. Conclusion

The system combines chemical soil testing methods, IoT-based sensor monitoring, and intelligent crop recommendation techniques to analyze soil conditions in real time. Different sensors such as NPK sensors, pH sensors, moisture sensors, temperature sensors, and color sensors are used to collect accurate soil and environmental data. The ESP32 microcontroller processes the sensor readings and transmits the data to a cloud-based dashboard using IoT communication technologies such as Wi-Fi or GSM.

The digital dashboard provides farmers with an easy-to-understand soil report, nutrient analysis, crop suggestions, and fertilizer recommendations. This makes the system practical even for farmers who may not have advanced technical knowledge. The portability and affordability of the system make it highly suitable for small-scale and rural farming applications.

The project also demonstrates the importance of integrating IoT and artificial intelligence in agriculture. Smart farming technologies can support precision agriculture by enabling real-time monitoring, automated analysis, and data-driven decision-making. The proposed system contributes toward sustainable agriculture practices by helping farmers use resources more efficiently and reduce environmental impact caused by excessive chemical usage.

One of the major strengths of the proposed system is its ability to recommend suitable crops based on soil nutrient levels and environmental conditions. By using rule-based logic and machine learning algorithms such as Random Forest, Decision Tree, and KNN, the system can help farmers select crops that are more suitable for their land and climatic conditions. This improves crop productivity, reduces fertilizer wastage, and increases farming profitability.

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Although the system provides several advantages, there are certain limitations such as sensor calibration requirements, internet dependency for cloud services, and maintenance of chemical testing solutions. However, these limitations can be improved in future versions through better sensor technology, offline support systems, and advanced AI integration.

In the future, the system can be enhanced by integrating weather forecasting, mobile applications, satellite monitoring, AI-based fertilizer prediction, and multilingual support for farmers. Advanced features such as drone-based monitoring and real-time farm analytics can further improve agricultural productivity and smart farming capabilities.

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