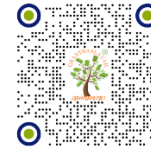


Original Article

AI-BASED SOIL HEALTH ANALYSIS AND CROP RECOMMENDATION SYSTEM FOR SMART FERTILIZER MANAGEMENT IN PRECISION AGRICULTURE

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ABSTRACT

Precision agriculture is changing the modern agriculture system by adopting the artificial intelligence (AI) technology that enhances the performance of agricultural systems and environmental conservation. The study introduces an artificial intelligence solution that assesses the state of soil and suggests farming methods to attain the most optimal use of fertilizers and enhanced crop production outcomes. The system employs machine learning algorithms to handle the key soil parameters that comprise pH, moisture levels, nutrient content and temperature readings. The system takes these inputs to decide the level of soil fertility as it also recommends the kind of crops and their particular requirements of fertilizer. The given model uses empirical data to pursue three goals that encompass the reduction of fertilizer use and minimization of environmental damage and the progress of more environmentally friendly practices in agriculture. The system will help farmers make prompt decisions as it will give them a smart system to communicate with. As demonstrated by the experiment, our system is superior when compared to the traditional methods, not only in terms of selecting crops precisely, but also with efficient nutrient management. The strategy will allow farmers to adopt clever farming practices that will offer them inexpensive and environmental-friendly practices that yield high agricultural yields.

Keywords: Artificial Intelligence, Precision Agriculture, Soil Health Analysis, Crop Recommendation, Smart Fertilizer Management, Machine Learning, Sustainable Farming, Nutrient Optimization, AgriTech Systems

INTRODUCTION

Agriculture acts as the foundational economic support system for the world economy because it supplies food needs and provides employment to billions of people. The agricultural sector face increasing difficulties because soil degradation and climate changes and excessive fertilizer use and reduced crop yields create problems for traditional farming methods. The agricultural system in India, which serves as a vital part of the country's economy, experiences common inefficiencies because its farmers lack access to real-time decision support systems while they waste resources. Advanced technologies, including Artificial Intelligence (AI), need to be integrated into agricultural systems because they provide essential support for sustainable and effective farming operations.

Precision agriculture functions as an innovative farming method that uses contemporary technological systems which include Internet of Things (IoT) and remote sensing and machine learning to enhance agricultural efficiency by controlling resource use and

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increasing crop yields. Through its data-driven insights, precision agriculture allows farmers to track soil conditions and weather patterns and crop health throughout the day. The most essential factor for determining agricultural productivity exists in soil health. The pH level and moisture content and temperature and nitrogen and phosphorus and potassium nutrient availability of soil determine how crops develop and produce their harvest [Lal \(2016\)](#). The conventional soil testing procedures require extensive time and physical work and they do not provide solutions for large-scale application.

Artificial Intelligence will be a good solution to these problems since it will allow conducting automated soil tests and implement smart decision-making procedures. The machine learning algorithms scan through large volumes of agricultural data that can allow them to identify trends that can be used to make correct predictions of soil fertility and crop suggestions according to real soil conditions. The findings of the research indicate that AI-based systems are more accurate with regard to predicting the crops and managing the resources than the traditional method of doing it [Kamilaris and Prenafeta-Boldú \(2018\)](#). The systems do not lose their capabilities to furnish the farmers with real-time environmental data which they can rely on to make decisions.

The most significant issue that the agricultural sector is currently grappling with is the situation in which farmers use excess fertilizer in the wrong proportions as it increases their cost of operation even as it kills the health of the soil and pollutes water bodies and damages the ecosystem. When farmers use excessive chemical fertilizers, they bring about harmful consequences which kill the microbes of the soil and cause irreversible deterioration in the soil health. Smart fertilizer management is one of the main elements of sustainable development plans used by the agricultural sector. The AI-based soil analysis systems are in collaboration with the crop recommendation systems, to determine the specific types and quantities of fertilizer that farmers should apply to meet their maximum crop production objectives. The specific approach is useful in reducing wastes even as it minimizes environmental degradation and improves efficiency in the farm operations [Chen et al. \(2020\)](#).

The recent years have witnessed the research activities that develop the intelligent agricultural systems that utilize the soil analysis in order to propose the crops. In these systems, supervised learning algorithms are used and these algorithms consist of decision trees and support vector machines and random forests that determine the types of soils and then predict the crops that will do well. Research is currently underway on the deep learning techniques that can allow specialists in the agriculture industry to discover trends and perform predictive analysis functions [Tripathi and Mishra \(2018\)](#). Most of the existing systems do not work as complete systems as they do not support multiple locations and they require instant access to information particularly in remote locations that are resource deficient.

The proposed research will solve these issues by establishing an AI-supported system of analyzing soil health and recommending crops to manage smartly through the use of the fertilizer. The system computes several soil characteristics to predict the degree of soil fertility as it recommends the type of crops and most effective practices in applying the fertilizers.

The solution is based on machine learning models and data analytics to develop an entire decision support system that assists with precision agriculture. The interface offered by the system is simple, and farmers are able to make correct decisions without any special technical skills.

This paper explores two key fields of research by investigating sustainable practices and environmental protection practices. This is because the proposed system helps in attaining environmentally friendly agricultural practices because it would reduce the use of fertilizers and enhance the distribution of nutrient within the agricultural fields.

The solution allows farmers to establish climate-sensitive agricultural systems that help them to cope with the changes in the environment as well as to establish the capacity to handle the extreme weather events. AI solutions use agricultural solutions that enhance productivity and natural resources and soil health [Sharma et al. \(2021\)](#).

The AI-based agricultural systems establish ecologically-friendly farming systems as they enhance efficiency in their operations. The proposed AI-based soil health analysis and crop recommendation system will answer the fundamental issues of traditional agriculture since it will give correct and data-driven information on the selection of crops and the application of fertilizers. The study contributes to precision agriculture by coming up with a method that can assist the farmers to increase crop production, but at the same time minimize their effects on the environment.

LITERATURE REVIEW

Artificial intelligence and machine learning technologies have become essential tools for agricultural assessments because they enable researchers to analyze soil conditions and determine suitable crops and optimize fertilizer application techniques. Researchers have developed intelligent systems which combine soil data and environmental factors with predictive models to enhance agricultural output and environmental sustainability. Several studies have shown that artificial intelligence-based soil analysis systems are now essential for modern farming.

The traditional methods of soil testing require extensive time and manual effort to complete, while AI-based methods provide immediate and exact soil testing results through technologies that include remote sensing and spectral analysis and predictive modeling [Awais et al. \(2024\)](#). The technologies enable farmers to obtain practical information that reveals soil nutrients and moisture content and pH values, which they use to make data-based decisions that lead to the best crop outcomes.

Machine learning technology based crop recommendation systems have emerged as a popular research topic over the last several years. Scholars have developed some models that deploy the algorithms of Random Forest and Support Vector Machines (SVM) and Decision Trees to examine the soil and climatic environments to select crops. The ML-based crop recommendation systems apply varied parameters that comprise of nitrogen and phosphorus and potassium (NPK) and temperature and humidity and rainfall to determine the most suitable regional crops to be grown [8]. The systems also allow the farmers to get a richer yield of crops as they reduce the probability of crop failures.

Deep learning techniques are more likely to be used due to the application of more accurate predictive techniques.

In one of the studies, they used the Long Short-Term Memory (LSTM) networks and ensemble models to train crop recommendation, which reached an accuracy of up to 92 percent to include the data of weather forecasting [Venkateswara et al. \(2025\)](#).

Deep learning models integrated in real-time applications of soil fertility prediction and crop selection comprise Multi-Layer Perceptron (MLP) and LSTM which are high precision and reliable performance as per research [Gunasekaran et al. \(2025\)](#). These solutions represent the increasing potential of AI to deal with any complicated agricultural data.

Table 1

Table 1 Literature Review Table				
Author (s) & Year	Methodology Used	Key Parameters	Findings	Limitations
Majdalawieh et al. (2025)	AI-based precision agriculture review	Crop health, disease detection	AI improves decision-making and productivity	Data dependency issues
Cheema et al. (2025)	AIoT-based nutrient analysis system	NPK values, soil properties	Accurate crop recommendation using sensor data	High implementation cost
Shastri et al. (2025)	Supervised ML for crop recommendation	Soil + climate data	Enhanced agricultural output using ML models	Needs large dataset
Shawon et al. (2025)	Ensemble & hybrid ML models	Weather + soil datasets	Improved prediction accuracy using hybrid models	Model complexity
Chaudhary et al. (2026)	Ensemble learning for soil fertility	Soil nutrients, pH	High accuracy in soil fertility prediction	Limited field validation
Sudha et al. (2026)	ML-based precision agriculture framework	Soil health, pest prediction	Real-time monitoring and predictive insights	Scalability challenges
Latha et al. (2025)	Deep Learning for soil nutrient prediction	Soil minerals, fertilizer usage	Accurate nutrient prediction and optimization	Requires high computational power
Dhanaraj et al. (2025)	Random Forest-based smart farming system	Environmental & soil factors	Optimized water and crop management	Limited fertilizer integration

The systems of fertilizer recommendations have been developed by applying artificial intelligence technology. Machine learning systems identify the nutrient composition of soils and needs of crops and prescribe the most suitable type and amount of fertilizers. Recent research states the importance of data-driven models in order to decrease the unwanted use of fertilizers and enhance nutrient efficiency that would lead to cost savings and environmental sustainability [Sundari et al. \(2025\)](#). The use of the AI-based systems also enhances the fertilizer management practices as well as reducing soil erosion and environmental pollution.

The use of IoT technology and the AI capabilities have enhanced the effectiveness of precision agriculture systems. The sensor networks use IoT to gather real-time information about soil moisture, temperature, and environmental conditions and then the ML algorithms process it to generate precise recommendations [AI-Driven Soil Monitoring and Crop Recommendation System Using Machine Learning Algorithm. \(2024\)](#). The system allows farmers to track the prevailing conditions which prevents them from making instant decisions as their agricultural practices are able to adapt to emerging environmental challenges.

Recent studies also look at multimodal AI systems that utilize the data of the soil and image search and environmental variables to provide superior outcomes of crop recommendations. Deep learning models that simultaneously classify soil images and nutrient profiles achieve an accuracy rate of 98 percent that indicates that the results of soil image and nutrient profile classification using multiple data sources is better in agricultural decision-making [Pandey et al. \(2025\)](#). The systems offer a comprehensive study of the health of soils and their crop growing capability.

The proposed system uses integrated AI technology to combine three functions which include crop recommendation and fertilizer optimization and disease detection to create complete agricultural solutions for farmers. The system operates by processing

three inputs which include soil nutrient data and weather information and crop condition data to enable farmers to manage their fields effectively while increasing their output [Artificial Intelligence-Based Crop Recommendation and Disease Detection System. \(2024\)](#). Performance upgrades in the system were enabled by disease detection modules infused with convoluted neural networks (CNN) for disease identification.

The development of AI-driven agricultural systems faces multiple obstacles which remain to be solved. The main barriers to adoption include data quality problems and model generalization issues and the shortage of necessary infrastructure and the restricted access to services in rural regions. The researchers have shown that real-world agricultural applications require solutions which must be easy to use and scale up while staying affordable [Gupta et al. \(2022\)](#). The use of explainable AI (XAI) techniques helps to build trust in AI recommendations through better explanation of system operations.

The research shows that AI-based systems for soil health evaluation and crop recommendation for farming purposes will transform agricultural practices through their capacity to boost crop output and enhance fertilizer efficiency and support eco-friendly farming methods. The existing methods require development of systems which can operate in real time and provide users with easy access to their functionalities. The researchers plan to create a complete AI solution for smart fertilizer management in precision agriculture to address existing research gaps [Reddy et al. \(2024\)](#).

METHODOLOGY

The proposed system utilizes artificial intelligence for soil health analysis and crop recommendation which will improve fertilizer use efficiency and boost agricultural production. The methodology follows a systematic pipeline which includes the data acquisition and preprocessing steps together with model development and prediction and recommendation development processes [Majdalawieh et al. \(2025\)](#).

The entire procedure, with help of which the proposed AI-based soil health evaluation and agriculture crop recommendation system, illustrated by the figure, functions. This is initiated by the collection of data that requires the soil parameters and the weathering data and past crop data to continue the process. The second step will involve data preprocessing that will apply the three processes which include cleaning, normalization, and feature selection to come up with the best input data.

Figure 1

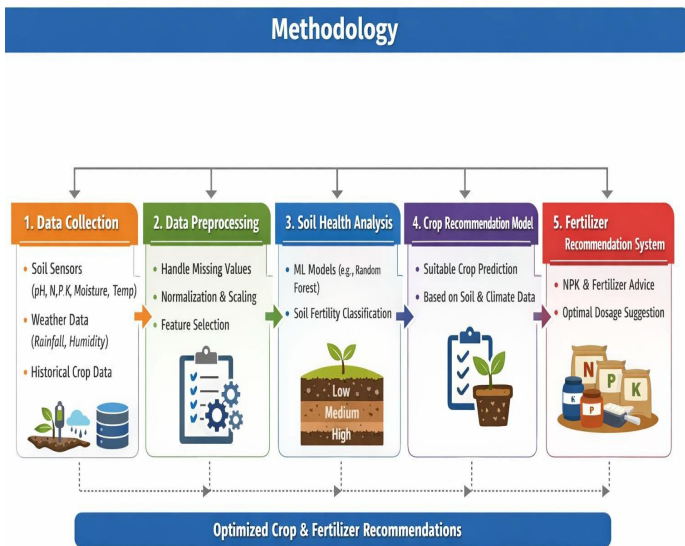


Figure 1 Methodology for Optimized Crop and Fertilizer Recommendations

Machine learning models can also be used to conduct soil health assessments that lead to the determination of various levels of fertility [20]. The crop recommendation model works on the basis of soil properties in conjunction with the prevailing climatic conditions in order to establish the type of crops to be planted. The system of fertilizer recommendations provides precise nutrient requirement advice along with information on the most appropriate way of applying the nutrient requirements. This approach contributes to the improved growth of crops as well as encourage safe use of fertilizers that cause positive effects on the environment.

DATA COLLECTION

The system must be able to gather the incoming data since the final suggestions will be based on this data that will dictate their specific outcomes. The authors of the present research gathered information using various reliable sources to define a proper concept of soil and environmental situation [Shawon et al. \(2025\)](#). The research team collects soil parameters that involve pH level and nitrogen (N) and phosphorus (P) and potassium (K) and moisture content and temperature either with the IoT-based soil sensor or available agricultural dataset. The research uses the soil information and the environmental factors such as the precipitation, humidity and climatic factors, as they have a high impact on crop development. The model requires historical crop data so that it can be refined in terms of learning abilities. As a result, the system will produce accurate soil analyses and give valid crop and fertilizer recommendations by utilizing the real-time sensor data with available datasets, and it will create a complete and informative dataset.

DATA PREPROCESSING

Collected data must be cleaned and organized by the researchers since it is the only way they can begin the work on the analysis. Machine learning models have problems with performance due to the fact real world data sets include missing values and irregular format and undesirable noise factors. The work on the collected data will start with the management of the missing and erroneous values using two approaches including the removal or replacing the data with appropriate estimated values [Sudha et al. \(2026\)](#). The standardization of parameters in data measurement, including normalization and scaling of pH, moisture, and nutrient levels, are crucial variables in determining the creation of standardized measurement procedures that enhance the stability and accuracy of the model. The most important soil and environmental variables affecting the development of crops are identified by feature selection. The process simplifies the model and increases its efficiency. Preprocessing of the data is a very important process that generates a dataset that satisfies the three main criteria: it should be clean, consistent and it should be useful in the construction of the correct predictive models.

SOIL HEALTH ANALYSIS

The system then analyzes the extent of soil conditions by its primary properties once it is done in preprocessing activities. The analysis of the pH content along with moisture content and nitrogen phosphorus potassium essential nutrients illustrates the overall assessment of the soil fertility. The proposed system uses machine learning models to identify patterns of data that will allow it to categorize soil into three levels of fertility - low, medium and high - rather than applying the conventional manual assessment systems [Chaudhary et al. \(2026\)](#). The system offers automated analysis to determine soil quality at a better speed and accurate findings. The system helps in decision-making by offering a good foundation through evaluation of soil health in the future. It can then present suitable crops and compute the most suitable amounts of fertilizer.

CROP RECOMMENDATION MODEL

The determination of sufficient crops to be planted starts after the analysis of soil health. During this process, machine learning models handle the properties of the soil and the environment factors in order to determine the crops that need specific requirements. The system would give highly precise recommendation depending on the inputs like the levels of nutrient (NPK) and pH and temperature and humidity and rainfall. This model utilizes past agricultural data to come up with its perception of the crops that would perform well in the identical conditions rather than relying on the general assumptions. With this approach farmers are able to select crops that are more suited to their land thereby reducing the chances of crop failure and increasing overall production [Latha et al. \(2025\)](#). The system offers evidence- based suggestions that see farmers make improved decisions regarding their farming practices.

FERTILIZER RECOMMENDATION SYSTEM

The system proceeds to recommend the appropriate fertilizer types and application rates after determining which crop will perform best in the given conditions. The system determines fertilizer application rates through scientific analysis of soil nutrient content which includes nitrogen and phosphorus and potassium measurements together with the specific nutrient needs of the chosen crop. The process of analysis determines the exact fertilizer needs, which helps to correct existing nutrient shortages. Farmers can use this method to determine the best fertilizer amounts. This helps them avoid using too much or too little fertilizer, which saves money and protects soil health and the environment. The system promotes sustainable farming by using a balanced way of managing nutrients, which leads to better crop yields [Dhanaraj et al. \(2025\)](#).

RESULT

The research compares multiple machine learning algorithms which scientists use to develop soil-based crop recommendation systems. The study assesses model performance through the accuracy results which previous research and current agricultural AI systems have provided.

Table 2

Table 2 Performance Comparison of different Models				
Model	Accuracy (%)	Precision (%)	Recall (%)	F1- Score (%)
Decision Tree	85%	83%	82%	82.50%
Support Vector Machine (SVM)	88%	86%	87%	86.50%
Random Forest	92%	91%	90%	90.50%
K-Nearest Neighbors (KNN)	87%	85%	84%	84.50%
Ensemble Model	95%	94%	93%	93.50%

The table provides a performance comparison of various machine learning models that are used for crop recommendation systems. The Ensemble Model outperforms all other models because it achieves better results in all assessment tests which measure accuracy and precision and recall and F1-score. The Random Forest model demonstrates strong performance because it achieves balanced results across multiple evaluation metrics. Decision Tree and K-Nearest Neighbors (KNN) models perform worse than current machine learning approaches. The results indicate that advanced hybrid machine learning methods will enhance prediction accuracy and decision-making capabilities in precision agriculture applications.

Figure 2

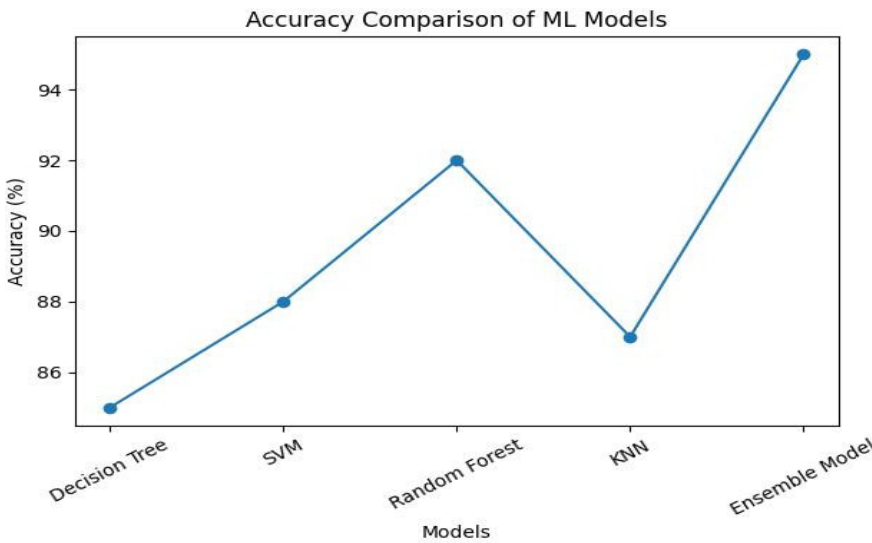
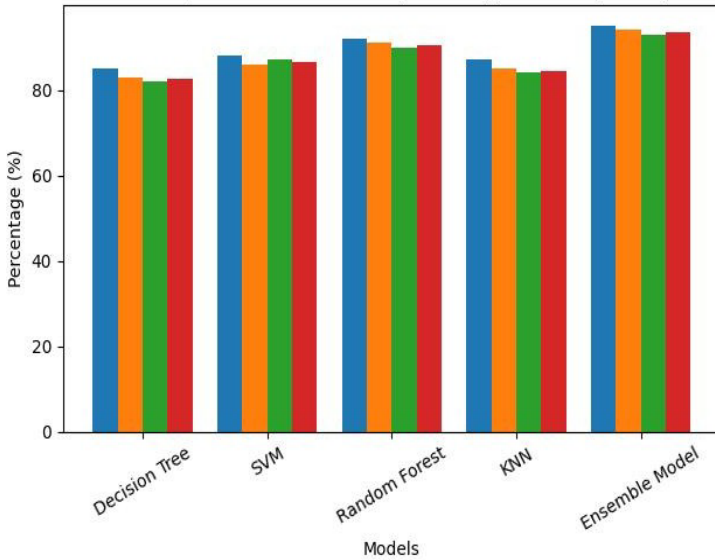


Figure 2 Accuracy Comparison of ML Models

The figure shows the comparison of accuracy among different machine learning models used in the system. The Ensemble Model achieves the highest accuracy while Random Forest and SVM show lower accuracy than that model. Decision Tree and KNN model performance needs improvement because advanced models deliver superior prediction accuracy for agricultural applications.

Figure 3

Performance Comparison of ML Models (Accuracy, Precision, Recall, F1-Score)

**Figure 3 Performance Comparison of ML Models**

The bar graph shows a comparison of different machine learning models, evaluating their performance using four key metrics: accuracy, precision, recall, and the F1-score. The Ensemble Model maintains the highest performance across all measurement standards which the Random Forest model follows in second place. The results show that advanced models deliver agricultural prediction systems which demonstrate better assessment results between different performance metrics.

CONCLUSION

This study illustrates an artificial intelligence approach to assess the health of soil to know the right type of crops that should be planted and the mode of fertilizing the soil. The developed system by the researchers applies soil parameters and environmental factors and machine learning methods to provide an efficient farm decision-making system. This approach will enable farmers to have data-driven information that will help them decide on crop choices and choice of fertilizer to use better than the traditional approaches that relied on general assumptions. The paper shows that higher models deliver better accuracy and reliability outcomes in the event of employing ensemble techniques. The system is beneficial to the sustainable agriculture sector as it reduces unnecessary use of fertilizers that in turn reduces costs but increases the production of crops. This solution can be implemented by farmers due to the fact that it only needs simple digital platforms. The study satisfies the growing need of intelligent agricultural practices that produce high yields and at the same time preserve the environment.

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