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AI-Based Smart Farming for Sustainable Agriculture: A Review of Techniques, Applications, Challenges, and Future Directions

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Abstract - The agriculture sector is vital for both food security and economic development. However, farmers are still struggling with issues like depletion of soil, disease in crops, unpredictable yields, high cost of cultivation, and market variations. The current farming practices are mostly governed by general recommendations and experience. The general recommendations or experience may not necessarily offer appropriate decisions for particular farms. Advancements in technology in the field of Artificial Intelligence (AI), Machine Learning (ML), and data analytics offer potentials to provide better decision making in agriculture. The present review focuses on use of AI based techniques in smart farming, with special reference to soil analysis, crop recommendation, fertilizer management, pest and disease identification, crop yield prediction, agricultural market forecasting. The paper also mentions the benefits and limitations of popularly used machine learning algorithms and data driven decision support systems. Further, it emphasizes importance of reliable agriculture datasets, model accuracy, cost effectiveness, data privacy, and accessibility to farmers. Finally, research opportunities are identified for development of integrated software based smart farming platform for sustainable agriculture practices and informed decision making.

Key Words: Artificial Intelligence, Smart Farming, Machine Learning, Precision Agriculture, Sustainable Agriculture, Crop Recommendation.

1. INTRODUCTION

Agriculture is one of the major sectors for sustenance, employment and economic development of human society by providing food, raw materials and livelihood to the vast population. In countries like India, agriculture is also very crucial for rural development. But there are many challenges in the agriculture sector. The agricultural sector is suffering from challenges like soil degradation, nutrient deficit, crop diseases, rising input costs, changing climatic conditions, and the uncertainty in the agricultural market, which influence crop productivity and farmers income. Generally, traditional agriculture practices are being conducted based on farmer's experience, local knowledge and conventional crop management practices. Though this information is very valuable, but it may not be sufficient to analyse complicated agricultural conditions. For example, in case of crop selection, many factors like soil properties, nutrient availability, soil pH, seasonal conditions and suitable crops in the local region have to be considered. Also, applying fertilizers without knowing the actual need of nutrients in the soil, may increase cost of cultivation and have negative impacts on environment. The emergence of Artificial Intelligence (AI) has brought new opportunities to meet these challenges. AI-based systems can be used to analyze large amounts of information about agriculture. They can detect patterns and provide predictive support for farming decisions. One form of AI is Machine Learning (ML) which allows computer systems to learn from existing data and offer results without the need for human to manually program each decision. An advanced form of ML is Deep Learning (DL). DL can detect complex patterns in images and other forms of agricultural data. For example, AI application areas have been studied in the last years on crop selection, soil fertility assessment, plant disease detection, fertilizer recommendation and crop yield estimation. With the help of AI, the farmer can make decisions based on information about agriculture, not just on general assumptions. Meanwhile, there is increasing interest in using machine learning methods in crop prediction and specific management for agriculture, as shown in research papers published in 2024 and 2025 [1-4]. Smart farming is about using digital technologies and analytical approaches to improve planning, monitoring and management of agricultural systems. This may involve software platforms where farmers can input soil information, analyze crops requirements, get advice for agriculture, estimate production, market trends, etc. Such a system can be very helpful if it is made in a simple interface and with accessible information. In this paper, the critical AI techniques applied in smart farming are discussed. The agriculture application of these techniques is investigated. Limitations of these techniques are discussed. Future research works for sustainable agriculture are highlighted.

2. REVIEW METHODOLOGY

This review is a literature-based study about the utilization of Artificial Intelligence and Machine Learning in smart farming. Relevant research works were considered from 2023 to 2025 to get an idea about the recent advancements and utilized techniques, agriculture applications and research challenges exist in this regard. Machine learning based crop recommendation, soil fertility estimation, fertilizer management, crop yield prediction, computer vision in agriculture and relevant research activities are investigated in the literature. The research papers published in journals such as Heliyon, Precision Agriculture, Smart Agricultural Technology, Engineering Applications of Artificial Intelligence are considered in this literature review. The literature review is conducted from the following perspective:

1. Identify the utilized AI and ML techniques in the agricultural application.
2. Soil-related and crop-related recommendation approaches are investigated.
3. Fertilizer management and crop yield prediction methods are investigated.
4. Benefits and limitations of current systems are explored.
5. Research gaps and future developments are explored.

A qualitative comparison of the selected studies is presented focusing on the objectives, methods and agricultural applications as well as the limitations mentioned in the studies. Note that this paper presents a narrative review rather than an exhaustive systematic review or conducting new agricultural experiments.

3. ARTIFICIAL INTELLIGENCE TECHNIQUES IN SMART FARMING

Artificial Intelligence offers various techniques for computational processing of agricultural information to support decision-making. The appropriate technique selection requires consideration of data type, agriculture problem and output expected.



Fig:1 – Architecture of an AI-Based Smart Farming System

3.1 Machine Learning

Machine Learning is a popular technique used in agriculture for prediction and classification. It is a technique that learns the relations between inputs and expected outputs based on prior data collection. Some of the datasets in agriculture may include information such as pH of soil, nitrogen, phosphorus, potassium, temperature, rainfall, humidity, type of crop and prior production information. Some popular ML algorithms that are commonly used are as follows:

- Decision Tree
- Random Forest
- Support Vector Machine
- K-Nearest Neighbours
- Gradient Boosting

Such algorithms can be used to determine appropriate crop selection, estimate agricultural production, and to examine information related to soil.

3.2 Deep Learning

Deep Learning uses multi-layer neural networks for finding complex relationships in large dataset. This is effective when the agricultural applications require image processing and pattern recognition. Convolutional Neural Networks (CNN) is widely used for plant image classification and disease detection. For sequential data such as historical weather and agricultural production data, we can use Recurrent Neural Networks (RNN) or Long Short-Term Memory (LSTM) networks.

3.3 Data Analytics

Data analytics refers to the process of collecting, analysing, and interpreting data of agricultural information. It helps discover the hidden patterns and relationships which are not easily identifiable with manual analysis. For smart farming, data analytics can be applied to historical crop production, soil report, cultivation expenses, and market price data. The combination of data analytics and machine learning can facilitate making better decisions in agriculture.

3.4 Predictive Modelling

Predictive modelling involves using past and present data to make predictions about future events. Applications of predictive modelling for agriculture are crop yield estimation, production planning, market price prediction and predicting possible crop-related risks. The accuracy of the predictions depends on the quality and relevance of data used as inputs, so it is necessary to assess the performance of the predictive models with suitable validation procedures before using their results in making agricultural decisions.

4. APPLICATIONS OF AI IN SMART FARMING

4.1 Soil Analysis and Fertility Assessment

The growth of crops and overall agricultural productivity is dependent upon the quality of soil. Some important soil parameters include nitrogen (N), phosphorus (P), potassium (K), pH, organic carbon, electrical conductivity and micronutrients.

Artificial intelligence based soil analysis systems can work with the information provided by the laboratory soil report and categorize the soil condition based on the amount of available nutrients. By using machine learning algorithms, it is possible to find the correlations between the soil characteristics and the requirements for agriculture. Digital analysis of the soil report can provide farmers with an easier way of understanding the results from the laboratory through simplified descriptions.

Using Optical Character Recognition (OCR), information from the uploaded soil report in PDF or image format can be extracted and values can be validated and analyzed through an analytical system. But, the reliability of the soil analysis depends on proper data extraction and the proper lab analysis. Sometimes, the wrongly computed nutrient value can result in improper recommendations. Thus, the proper validation of extracted soil information is a crucial part of a good soil analysis system.

4.2 AI-Based Crop Recommendation

One of the critical points in agriculture planning is to choose the proper crop. Various crops have different soil requirements. It has different nutrient requirements. One good crop from one place might not be so good in another area. AI-based crop recommendation systems look for possible options of crops based on agricultural parameters like soil pH, nitrogen, phosphorus, potassium, temperature, rainfall, humidity.

Machine learning classification algorithms can help to compare with the learned patterns from agricultural datasets. Based on input conditions, the machine can give you proper ranks for possible proper crops. A research paper was published in 2024 on Indian Agriculture and horticulture crop recommendation by some researchers. They studied some machine learning models for NPK value, soil pH, temperature, rainfall, humidity [1]. The work shows how useful the combination of soil and environmental information can be to choose a crop. However, one must be aware of regional suitability, seed availability, cultivation time, availability of water resources and local agricultural practices for the crop suggestions. One should not expect the prediction based on limited data to be the outcome of production.

4.3 Fertilizer Recommendation

Applying fertilizer is important for providing key nutrients that are needed for crop growth. But over-or under-application

of fertilizer can influence the cost of production, soil conditions and environmental conditions. Fertilizer recommendation systems that are based on artificial intelligence can analyse information about soil nutrients and crop needs to suggest potential shortages of nutrients.

Machine learning models can help with estimation of possible fertilizer options and application requirements. Research on agricultural input management application of different machine learning approaches such as Random Forest, Support Vector Regression, XGBoost, Artificial Neural Networks is studied. Tanaka et al. (2024) studied the impact of different machine learning algorithms and combination of soil variables on fertilizer recommendation for site specific application [2]. The outcome of this study emphasises one important aspect that even though the model may predict crop yield accurately it need not be accurate for recommending fertilizer application. This emphasises the importance of validating the predictions that are related to fertilizer application. It is important that a good fertilizer advisory system should provide information on what nutrients could be short, why does it give such recommendations and what are the situations where lab or agriculture expert verification is needed.

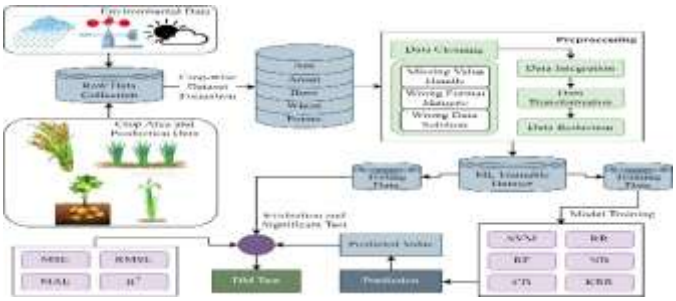


Fig:2 – Machine Learning Process for Crop Recommendation

4.4 Pesticide Advisory and Plant Disease Identification

Crop diseases and pests attack can result in a reduction in the agricultural production, and possibly, the crop quality. It is important to detect diseases and pests as early as possible, otherwise, it could result in further damage of the crop. Machine learning and computer vision methods can be used to analyze images of plants to identify visible symptoms of certain diseases.

Using CNN based classfication models, it is possible to learn the visual patterns like spots on the leaves, change of color, damage areas, unusual patterns on plants. AI based pesticade advisory systems might combine the information on disease identification, as well as information about the crop and proven agricultural advice. The advice is designed to provide the information to farmers on possible control methods, and avoid unnecessary use of pesticides. Nevertheless, the prediction from images could be subject to lighting conditions, quality of the image, background objects, similarity between different diseases of plants. For this reason, the system should provide information about the confidence of prediction, and recommend expert verification for the cases, when we cannot be sure about prediction.

The recommendation for pesticides should include information about approved product, crop, pest, application guidance, and regulations in agriculture. AI predictions should not substitute professional advice in agriculture.

4.5 Crop Yield Prediction

Crop yield prediction is a significant application of machine learning in agriculture. It can provide an estimate of the potential amount of agricultural production using past and current information about farming.

The productivity of crops is influenced by multiple factors like soil fertility, crop type, rainfall, temperature, nutrient availability, cultivation practices, and disease conditions. Machine learning algorithms can be used to analyze these factors to predict the production. Some of the popular methods are Random Forest Regression, Linear Regression, Support Vector Regression, XGBoost, and Artificial Neural Network. Jabed and Murad (2024) have presented a review on machine learning and deep learning methods for crop yield prediction to understand their relevance to the agricultural sustainability [3]. In another recent systematic literature review, there is an emphasis on use of machine learning techniques and different attributes of agriculture for crop yield prediction (2025) [4]. Prediction of the crop yield can help farmers to assess the production, plan resource utilization, and be ready for potential market requirements. But it may differ for different regions, crop, and season. Also, reliable data and proper model validation are necessary for a good prediction.

4.6 Agricultural Market and Price Forecasting

For farmers, the market information is quite crucial as crop prices directly impact the agricultural income. The crop price is subject to variations due to different factors like variation in demand and supply, transportation, seasonal availability, and market conditions.

AI-based market analysis can look at the historic market prices, type of crop, market locations, and available information related to agricultural trading. The time series forecasting method can help identify the past patterns and predict the possible future price changes. These systems could assist farmers with the comparison of market information and the scheduling of the selling of crop produce. Many things are beyond our control when it comes to the workings of agricultural markets. So, it is advisable to express the forecast as an estimate, rather than a promise of future price. It is important that the data from the market is verified and updated for the reliable market price analysis. It is also important that the difference between reported prices and predicted values should be made quite clear in these systems.



Fig:3 – Applications of AI in Sustainable Agriculture

4.7 Cost and Profit Estimation

Agricultural decision-making is not only about the crop productivity, but also about the cost of cultivation and the return. AI assisted financial analysis can take data on seeds,

fertilizers, pesticides, labor, transportation, expected production, etc. and then estimate the total cultivation cost, possible revenue, and approximate profit with the help of a decision support platform for all these inputs.
This estimation helps farmers to have a better idea on what crops to choose (before cultivation). But the actual financial outcome is the result of actual production, market price, additional expenses, local conditions, etc.

5. COMPARATIVE ANALYSIS OF AI TECHNIQUES

Different AI techniques provide different benefits for different agricultural tasks. All the algorithms are not suitable for every farming task.

Table 1: Comparison of AI techniques used in smart farming

AI technique	Agricultural application	Main advantage	Major limitation
Decision Tree	Crop classification	Easy to understand	Can overfit
Random Forest	Crop and yield prediction	Handles complex relationships	Requires appropriate training data
Support Vector Machine	Crop and disease classification	Effective for classification tasks	Parameter selection can be difficult
XGBoost	Yield and agricultural prediction	Handles structured datasets effectively	Requires model tuning
CNN	Plant disease identification	Learns image features	Requires labelled images
LSTM	Historical yield and price analysis	Learns sequential patterns	Requires sufficient sequential data
Linear Regression	Cost and yield estimation	Simple and interpretable	Limited for complex relationships

It can be seen from the comparison that algorithm selection should be made as per the problem in agriculture and available dataset. Classification model is best suited for category identification, whereas, generally, regression model is used for estimation of any numerical value. Deep learning techniques are better for any image related tasks, but can demand more computation and require more labelled data sets.

6. CHALLENGES AND LIMITATIONS

Even though AI has huge potential in agriculture, there are certain issues that impact actual implementation of AI in agriculture.

6.1 Data Quality and Availability

Data quality plays a vital role in the performance of AI model. If training data are not complete, not accurate, not up to date, and imbalanced. It can affect the reliability of prediction in agriculture. Moreover, there are differences in agricultural conditions in each area, thus it is challenging to make it general.

6.2 Regional Differences

There are variations in soil conditions, types of crops, farming techniques, and seasons, thus it differs in each region. A model trained in one area might not be reliable in another area. Thus, it needs to be tested in different areas. It is also important to use data that are available in that particular area.

6.3 Cost and Accessibility

Some advanced AI solutions might need complex calculations and require advanced expertise. Sometimes, it can be a challenge for small farmers to access a complex and expensive platform. Thus, it is important to develop software that is affordable with simple UI/UX.

6.4 Lack of explainability

Some machine learning and deep learning model are complex prediction engines. People may get a prediction without any reason why it happens. Therefore, it is important to use Explainable Artificial Intelligence (XAI) to make it more transparent. We need to know the factors that impact the prediction.

6.5 Data Security and Privacy

Digital agriculture platform might hold soil reports, farm information, production information, and financial data. Inappropriate data handling can lead to a privacy and security issue. It is important to have proper authentication, access control, safe storage, and good data handling practices.

6.6 Model Reliability

The high predictive score does not necessarily guarantee the usability of AI system in real agricultural applications. Misleading recommendations for fertilizers, pesticides and crop selection can have economic and environmental effects. The models should be tested with independent data and evaluated for different agricultural scenarios.

7. FUTURE DIRECTIONS

Future smart farming will emphasize the improvement of reliability, understandability and accessibility of AI-based agricultural systems.

7.1 Integrated Agricultural Decision-Support Platforms

Future systems may bring together soil analysis, crop recommendation, fertilizer advisory, pesticide guidance, yield prediction, financial estimation in the same software platform. This would allow avoiding the multiple application requirement for various agricultural activities.

7.2 Explainable AI-Based Recommendations

Further research should highlight the reasons behind AI recommendation. Not just crop or fertilizer prediction, it should show the reasons behind the prediction. For example, which soil characteristics or agriculture conditions that were decisive for the prediction.

7.3 Improved Soil-Report Processing

OCR, document processing methods should improve for accurate extraction of agricultural parameters from laboratory reports. Future system should introduce data validation, confidence assessment, manual correction facility to minimize the errors.

7.4 Region-Specific Agricultural Models

With regional-specific datasets, the recommendation can be even more appropriate. Factors such as region-specific soil, crop variety, agricultural practices, historical production can be taken into account for the research.

7.5 Multilingual and Farmer-Friendly Interfaces

A fundamental aspect of the practical utility of digital agriculture is the language accessibility. The futuristic system must be accessible in regional languages. Further, it should be

based on simple and understandable terms rather than complicated technical jargon.

7.6 Sustainable Agricultural Decision-Making

The upcoming AI systems must focus not only on the agricultural productivity but also on the environmental impacts. For instance, the recommendations should be in favour of balanced nutrient management, responsible use of pesticides, reduce unnecessary use of inputs, make better use of available resources.

8. CONCLUSION

Artificial Intelligence and Machine learning have provided new dimensions for making better decisions and practicing sustainable agriculture. In this review, we discussed the applications of these techniques for soil analysis, crop recommendation, fertilizer management, pesticide advisory, disease identification, yield prediction, market price forecast and cost of cultivation estimation. From our review, the studies suggest that the use of machine learning algorithms can identify useful patterns from the data and aid various important activities in agriculture. Further, deep learning techniques offer a way to analyse the images of the plants for identifying the issues related to crop. However, the effectiveness of all these techniques depends on the quality of data, its regional suitability, model validation and trustworthiness of recommendations.

Many challenges are still exist especially regarding access to data, cost, transparency, privacy and usability. These limitations suggest the importance of developing agricultural systems that offer clear recommendations and that can clearly convey uncertainty.

The future research should focus on the integrated software based agricultural platforms, which have to cover the different AI applications together in a farmer friendly environment. The proposed agricultural platforms must incorporate verified agricultural information, explainable prediction methods and region specific datasets. If, AI based smart farming is developed and validated in a responsible manner, it can help for improving agricultural planning, efficient use of resources and sustainable farming practices.

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