Grenze International Journal of Engineering and Technology, June Issue

An Explainable AI-Driven Web Platform for Crop Yield Prediction and Crop Recommendation using Soil and Environmental Parameters

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***Abstract*— Impact of climate change on agricultural productivity in India has been increasingly severe, compromising crop yield stability and food security. Prediction of crop yield before the start of harvest season can play an important role for farmers to make better-informed decisions on crop storage, distribution and market strategies. To this end, in this research effort, we propose an integrated, hybrid and explainable Machine Learning (ML)-based framework for crop yield prediction and crop recommendation. Our proposed model goes beyond the traditional models by introducing a hybrid ensemble model of Random Forest (RF) and XGBoost (XGB) along with temporal trend analysis for climatic variables in order to capture trend variability for each season. The input parameters considered include temperature, humidity, rainfall, soil nutrients (Nitrogen, Phosphorus and Potassium) and historical yield trends that are used to enhance the predictive performance. The proposed model incorporates Explainable AI (XAI) for transparent explanations of the predictions based on SHAP (SHapley Additive exPlanations). Our web-based GUI has been designed to be accessible to all farmers with minimum technical knowledge. The proposed system predicts crop yield and recommends the best crop based on environmental and soil conditions using classification models (RF, Support Vector Machines, k-Nearest Neighbors & XGB classifiers). Experimental results confirm that the proposed hybrid model performs significantly better than the other standalone models, by improving predictive accuracy, robustness and generalizability. This research effort contributes to precision agriculture by providing an integrated, explainable predictive analytics system to assist farmers in their decision making.**

***Keywords*— Machine Learning, Random Forest Algorithm, Crop Yield Prediction, Crop Recommendation System.**

I. INTRODUCTION

Agriculture provides substantial contributions to both employment and India's GDP. A significant portion of India's population derives its income from agriculture. Agricultural productivity however is influenced by weather conditions (rainfall, temperature, humidity etc.) and soil quality [12][15]. These factors have been made even less predictable due to the effects of global warming that have developed over the last few decades, creating large swings in crop yield and increasing farmer risks. Historically, farmers were able to make educated guesses about how many crops they could grow based upon years of past experience and observation.

Grenze ID: 01.GIJET.12.2.117_26

The traditional methods used to estimate crop yields and to determine what type of crop to plant (based upon prior knowledge) can be ineffective at capturing all of the complexities associated with the inter-relationships between various independent variables.

Climate change is affecting the overall production of India's agricultural sector negatively as well as decreasing the yields of many different types of crops over the last twenty years[8]. Farmers and policymakers would greatly benefit from using accurate pre-harvest crop prediction models to make educated decisions for both their crop storage and market selling strategies. The project will develop a prototype version of an interactive predictive model with a user-friendly, web-based GUI (Graphical User Interface), which will utilize a Machine Learning program for its data analysis and result predictions. Once the predictive result(s) are generated they will be displayed back to the farmer, providing them with enough information to allow for intelligent agricultural planning and ensure both food security and sustainable farming practices.

So, for this type of analysis using big data in agricultural crop prediction, there are several methods or algorithms; and with the use of these algorithms, we can forecast the crop yield. The Random Forest algorithm has been used. Through the analysis of agricultural challenges such as weather variability, temperature fluctuations, humidity, rainfall, and soil moisture, it was identified that existing technological solutions remain insufficient to effectively address these issues. There are a lot of ways in which India could enhance its economic development within the realm of agriculture. Data mining is a good method for predicting crop yield production. Data mining is generally defined as the examination of large amounts of data from multiple perspectives and the summarization of this data into meaningful information, forming the foundation of modern agricultural analytics and automation[10].

Random Forest is one of the most popular and powerful supervised Machine Learning algorithms, which can perform both classification and regression tasks[3], and work by creating an ensemble of decision trees during the training process and generate output based on the mode of the classes (for classification) or mean prediction (for regression) of the individual trees.

II. Related Work

Accurate crop yield prediction and intelligent crop recommendation are critical challenges in modern agriculture, especially in countries like India where farming is highly dependent on climatic and soil conditions.

Several studies have explored the use of Machine Learning, data mining, ensemble models, and precision agriculture techniques to improve agricultural decision-making. This section reviews existing research related to Machine Learning-based crop yield prediction, ensemble and hybrid models, soil and climatic data analysis, crop recommendation systems, and highlights the research gap that motivates the proposed work.

A. Machine Learning for Crop Yield Prediction

Historical agricultural and climatic data are being put to good use, and one of the most impressive techniques out there is Random Forest, when using Machine Learning to forecast crop yields. Random Forest is an algorithm that can efficiently manage large, complex datasets and take into account multiple factors, and, according to a study in Tamil Nadu, Random Forest predictions were highly accurate. In a comparison with traditional Multiple Linear Regression, Random Forest showed it was the better of the two, at both the regional and global levels[3].

B. Ensemble and Hybrid Learning Models in Agriculture

Ensemble Machine Learning methods combine the results of multiple Machine Learning algorithms to enhance the overall predictive power of an ensemble[7][13]. The application of ensemble techniques has been examined in other research (e.g., ensemble methods including AdaNaive and AdaSVM for predicting crop yields) with researchers finding that boosting can increase the performance of standard classification models (e.g., Naive Bayes and SVM). Ensemble-based models also have been shown to have reduced error rates in prediction and improved generalizability relative to non-ensemble-based models[7]. Therefore, it appears that the use of multiple classification models will result in more accurate and reliable crop yield forecasting than would be expected from a single model, in improving prediction robustness.

C. Climatic Parameter-Based Yield Forecasting

Variables of climate (temperature, humidity, cloud cover, rainfall, vapor pressure) play a very large role in the overall production and health of crops[12]. The development of web-based Decision Support Systems using decision trees has been used by some researchers to determine how various climatic conditions affect crop yields in specific regions (Madhya Pradesh). These researchers concluded the need to identify important weather factors that directly contribute to crop performance. The accuracy of crop yield prediction models can be improved as additional research supports the idea that climatic related factors can be input factors.[12][16]. This is especially true for regions where crop production relies on precipitation, as climatic parameters such as rainfall, temperature, and humidity significantly affect crop yield.

D. Soil Analysis and Crop Recommendation Systems

Crop growth and production is heavily influenced by the characteristics of the soil in which it grows as well as the chemical makeup of the soil's nutrients [14]. Researchers have attempted to address issues with current soil testing procedures through developing a data driven process for providing crop and fertilizer recommendations. They found that poor or inaccurate soil test results can lead to selecting the wrong crops and lower crop yields. Data mining techniques to analyze soil and environmental parameters showed that using smart soil based crop recommendations can increase crop yields. These studies show the need for inclusion of soil nutrients such as nitrogen (N), phosphorus (P), and potassium (K) into crop suitability and recommendation systems[9][14].

E. Precision Agriculture and Advanced Machine Learning Techniques

Machine Learning Techniques like SVM, KNN and Image Analysis are increasingly being used in Agricultural Research[4] in addition to the Traditional Prediction Models. Machine Learning has been shown to be useful in Identifying and Classifying Soil Regions, Crop Regions and Vegetation Regions from Images and Sensor Data.
Machine Learning in Agriculture use has been documented in a number of Comprehensively Surveyed Reviews that show Ensemble Methods (such as SVM) can manage Complex and Large Scale Datasets in Agricultural Model. Additionally, Precision Agriculture Systems which utilize Remote Sensing and Aerial Platforms to Assess Crop Stress, Irrigation Practices and Yield Variability utilize Ensemble Methods to make More Informed Agricultural Decisions[4].

F. Research Gap and Motivation

Despite significant progress in crop yield prediction and crop recommendation framework, there is still much to be done. Several challenges exist with many current crop yield models using very large, regional or global datasets that can't capture the specific agriculture conditions that exist at the district/local level. Most systems also currently offer either crop yield prediction or crop recommendation in separate platforms rather than offering both functions in a single platform. In addition, an important limitation exists due to the lack of comparison of performance of different Machine Learning models to assist in selecting the best method(s) for accurate estimation.
Many of the previous solutions also don't have simple, farmer friendly interfaces that limit their use in practical applications. To address these limitations, the proposed system will emphasize the use of district-level data from Karnataka State (India), evaluate the performance of multiple Machine Learning methods including Random Forest, Support Vector Machines (SVM), k-Nearest Neighbour (KNN), and linear regression, and provide both crop yield estimation and crop recommendation in a single, user-friendly web-based interface.

III. PROPOSED FRAMEWORK

The Proposed System focuses mainly on localised data at district level in Karnataka State unlike the existing system which focused on various data which was varying for different regions. The Proposed System uses different climatic conditions, analyses the environmental conditions and soil composition by the geographically specific dataset at district level which is fed by the system. Machine learning is used to predict the crop which is suitable according to climatic conditions and gives accurate crop yield prediction.

A. Architecture of the Proposed Framework

The main aim of the proposed system was to improve the crop yield prediction and crop selection by analysing localised data at district level of Karnataka state. Many existing system failed due to taking the dataset from multiple regions which was the reason for lot of variations in the crop yield detection. This system was more accurate and exhibited enhanced performance by emphasising more on localised data, properties of the soil, climatic conditions of the environment, and comparing various Machine Learning models for correct prediction.
The architecture of the system shown in the fig.1 demonstrates how system combines Machine Learning models, database at the back-end and web-based user interface. Random Forest algorithm was selected as the prediction engine because of its robustness, reliability, and the capability to deal more complex and non-linear agricultural data. The application is designed to ensure smooth interaction between farmers, prediction modules, and administrators.

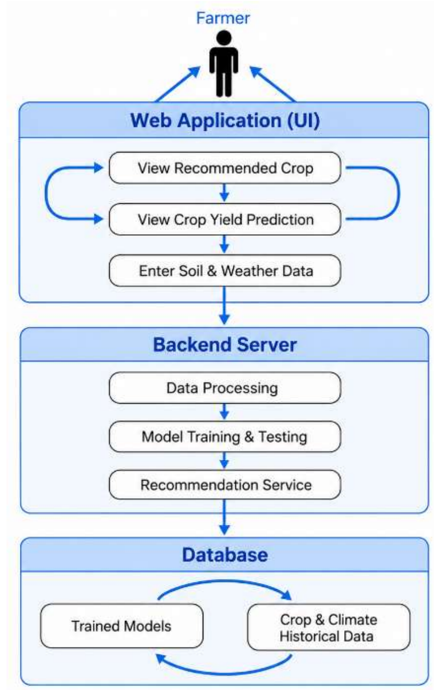

Fig.1. Architecture of the Crop Yield Prediction System

B. Forensic Data Acquisition and Preprocessing

Forensic Agricultural data is gathered from sources which are trusted such as meteorological records, reports of soil testing, and historical crop yield datasets. The system is designed to use these inputs mainly:

- Nutrient values of soil like Potassium (K), Phosphorus(P), and Nitrogen(N)
- Environment factors which can affect crop yield like humidity, rainfall, temperature, and precipitation[2].
- Geographic and historical data like district, state, and crop patterns from previous data

The dataset of the model undergoes preprocessing for improving the quality of the data before training Machine Learning models. Further inconsistent and incomplete records are removed, values which are missing are handled carefully and only features which are most relevant are selected. Categorical attributes such as crop type or state are converted to numerical values so that model can process them effectively. Preprocessing of this data is effective for the model to take the data in required format.

The dataset can be represented as:

$$D = \{(x_i, y_i)\}_{i=1}^{N}, \;\; \hat{y_i} = f(x_i), \quad f: R^d \to R \qquad (1)$$

here X denotes input features related to climate and soil, and Y represents corresponding crop categories and yield values and D represents data.

C. Crop Yield Prediction Using Random Forest

An ensemble learning techniques called Random Forest algorithm based on multiple decision trees is implemented in yield prediction module. For more accurate and timely prediction instead of using single model, Random Forest collects the output of several decision trees. Every decision tree is made to train on random data and features subset. Majority voting mechanism gives the final output, where each class is predicted by the highest number of trees. This class is selected as final result for classification tasks.

$$\hat{y}(x) = mode\{h_1(x), h_2(x), \dots, h_M(x)\} \qquad (2)$$

where:

- $\hat{y}(x)$ represents the predicted output
- $M$is the number of decision trees
- $h_M(x)$ is the prediction of the M^{th}tree

To reduce overfitting, variations and noise in the data this ensemble technique is used, making it well suitable for agricultural dataset and improving prediction accuracy.

$$\text{Loss function} \quad L = \frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2 \qquad (3)$$

D. Crop Recommendation Module

The Crop Recommendation Module is made for helping farmers in selection of most suitable crop for cultivation under specific environmental conditions and soil parameters[1]. This module serves as an effective decision support component for the end users since it uses data driven analysis to recommend crops that are expected to yield better economic and productivity returns unlike traditional practices that rely on experience-based decision making.

Objective

The main objective of the module is to identify the crop that is most suitable with the given soil composition and climatic conditions of a particular region. This system enhances sustainable farming practices and reduces the risk associated with improper crop choice by scientifically analysing parameters and aligning crop selection.

Methodology

The module takes environmental parameters as input like temperature, atmospheric pressure and humidity, along with soil nutrient content such as Phosphorus (P), Potassium (K) and Nitrogen(N). These inputs after comparative evaluation with different classification models are processed by Random Forest Classifier which provides higher accuracy.

Random Forest was preferred because it handles high dimensional data, avoids overfitting, and shows strong classification performance on non-linear data[6]. The model analyses patterns from historical agricultural records and predicts the class of crop which perfectly matches the provided input conditions.

The goal of this module is to recommended a crop that is best for the provided combination of soil and climatic parameters. The system also provides supporting information such as expected yield trend or suitability score in addition to the crop name which helps farmers to understand the reason behind the recommendation.

E. Web-Based System Implementation

The proposed system is implemented as a web-based application that can be accessed by both farmers and system administrators ensuring ease of use and accessibility. The system is designed to deliver accurate predictions and recommendations while minimizing technical complexity.

User Interface Design

The system provides two separate interfaces:

Farmer Interface

The end user interface allows farmers to enter agricultural parameters, soil type, nutrient concentration, temperature, humidity, and rainfall as details in simple and clearly structured format. After the submission of these details, the system will display the best crop and yield of the predicted crop in a understandable format for cultivators using graphs and comparative charts.

Admin Interface

The admin interface is responsible for managing the data and maintain the system. Administrators have authority to manage user accounts, monitor model performance, include new datasets, and can also initiate to retrain the model when the updated data becomes available. This will make sure that system relevant, consistent, and accurate over time.

Back-end Processing

The back-end is developed using python Flask, while the front-end of the application is developed using HTML, CSS, and JavaScript. MySQL is used as database to store datasets, credentials and prediction results. Upon authentication of user, the back-end will process input data, forwards it to the Machine Learning model, and returns the predicted results to the front-end interface.

F. System Workflow and Data Processing

The Workflow of the system begins with user logging into the web application (farmer or administrator). After authentication the user can choose between the two main options: Crop Yield Prediction and Crop Recommendation.

If the farmer selects the yield prediction option, a form is displayed where the farmer is requested to input soil texture, humidity, rainfall, temperature and nutrient concentration. The data is then sent to back-end for further processing where it is validated and formatted before sending to Random Forest Classifier model for prediction. If the recommended crop option is selected the system will prompt the user to enter the details like soil parameters and environmental conditions. Then the back-end will process the data and queries the trained classification model, which then gives most suitable crop according the input provided.
The prediction results are then sent to front-end and displayed according to farmer friendly model in am intuitive way.

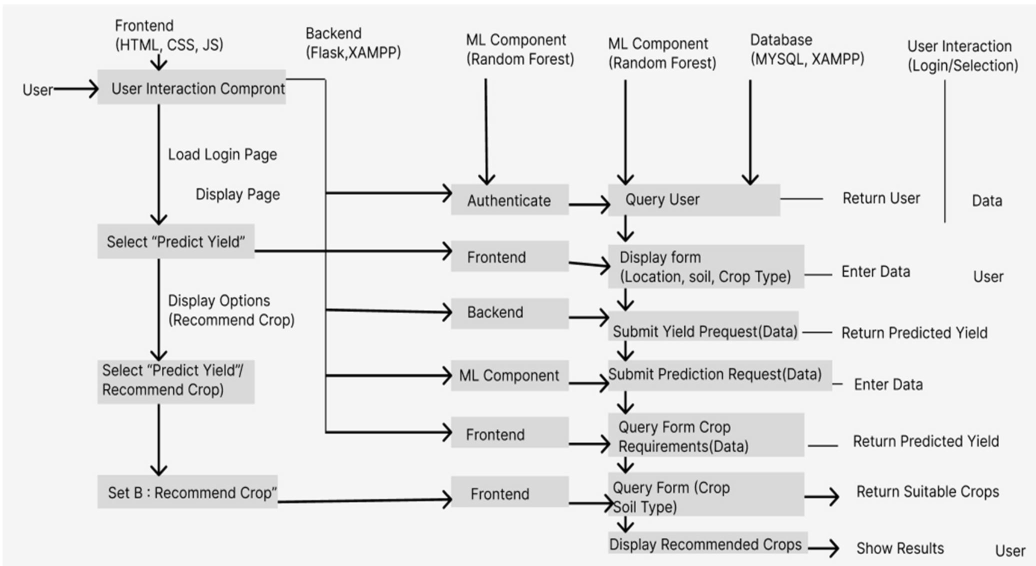

Fig.2. Sequence Diagram of the Crop Yield Prediction and Recommendation System

The Sequence Diagram shown in the fig 2 illustrates the workflow of the proposed system of crop yield prediction and recommendation. The process starts with user friendly interface where user can access the web application and logs in through the front-end interface of the system. After successful authentication , the user can select either crop yield or crop recommendation option. Relevant soil and environmental data are then entered and forwarded to the back-end for processing. The fig 2 shows the back-end passes the validated inputs to the Random Forest model for carrying out the analysis. The model generates predictions or suitable crop suggestions on the basis of learned patterns from historical data. These results are sent back to the user interface and displayed in a clear and understandable format to support effective agricultural decisions.

IV. IMPLEMENTATION

The entire process has been done in the Python programming language and integrated with web-based interface to offer farmers with crop yield prediction in real time as well as crop suggestion. The input variables made up of soil nutrient like Nitrogen (N), Phosphorus(P) and Potassium (K) and environmental parameters like temperature, humidity, rainfall and pH . The entry data gets prepared by means of utilising Pandas and NumPy to clean it up: missing data, normalizations of data, ensuring consistency of features to increase prediction quality etc Has been shown through previous research.
The implementation of a unified hybrid model was developed by integrating Random Forest and XGBoost to create a more accurate and robust prediction model. Random forest model identifies complex non linear relationships and XGBoost model improves prediction performance based on boosting .The final prediction is given by a weighted ensemble as:

$$\hat{y} = \alpha y RF + (1 - \alpha) y XGB \text{ ---------(4)}$$

where y_RFand y_XGBare are the predictions made by each of the models. The models were trained with the Scikit-learn library using an 80:20 split, K-fold cross validation, and hyperparameter tuning with GridSearchCV. The web app has been built with Flask, and the user interface has been built using HTML, CSS, and JavaScript.

Cultivators can enter their soil and weather conditions into the web application and receive their agricultural yield prediction immediately. To help make this process transparent to farmers, Explainable Artificial Intelligence (XAI) has been employed through the use of SHAP (Shapley Additive Explanations) to illustrate how important different features were in determining predictions. Matplotlib was used to generate visualizations of the results which should be easy to understand, and therefore will provide an excellent tool for farmers who are making decisions about agriculture in the real world.

V. RESULTS AND DISCUSSION

We used real agricultural and environmental data to evaluate the proposed system for its use in crop yield prediction and crop recommendation. The evaluation consisted of assessing the accuracy of the systems' predictions and the appropriateness of suggested crop recommendations and the accuracy of the various Machine Learning models being used is also compared. Evaluation criteria are similar across agricultural analytics based on recent studies. The results indicate that this system accurately, consistently, and reliably predicts crop yield and that the recommended crops are suitable to the soil characteristics and climate of the region, providing farmers with the ability to make informed decisions when selecting their crops.

A. Dataset Description

The dataset used for evaluation is available at the government's agricultural portal and meteorological sources from Karnataka. Each dataset included historical yield data integrated with soil and environmental information for 22 individual districts in Karnataka. As indicated in the table below, studies demonstrate that datasets created for regional purposes enhance the accuracy of prediction within an agricultural system. The datasets contain 15 variables which are commonly used to predict agricultural productivity including temperature, humidity, rainfall, soil moisture data, and the amount of essential nutrients, bonds/alkali trifluorides [N,P,K] needed for plant growth. The dataset available is approximately 21,124 records relating to different crops planted and harvested and the average yield from each crop over time for all four seasons in the entirety of Karnataka State. Each record is mapped to a yield value (in tonnes per hectare) and a corresponding crop label for recommendation.

TABLE I. FORENSIC DATASET STATISTICS

Feature	Value
Total Records	21124
Total Features	15
Crop Types	164
Region Covered	Karnataka (District-level)
Soil Parameters	Nitrogen (N), Phosphorus (P), Potassium (K)
Environmental Parameters	Temperature, Humidity, Rainfall

B. Performance Evaluation Metrics

The evaluation of this method consists of applying common Machine Learning metrics (classification and prediction) to evaluate both predictions and classifications. The metrics tabulated in this figure are typically used to measure accuracy and reliability of predictive modelling and classification problems. The summary of evaluation metrics used in this study is listed in Table II:

TABLE II. PERFORMANCE EVALUATION METRICS

Metric	Formula	Description
Accuracy	$\frac{TP + TN}{TP + TN + FP + FN}$	Measures overall detection performance
Precision	$\frac{TP}{TP + FP}$	Identifies correctly classified tampered records
Recall	$\frac{TP}{TP + FN}$	Measures sensitivity to detecting tampered forensic records
F1-Score	$2 \times \frac{Precision \times Recall}{Precision + Recall}$	Harmonic Mean of Precision and Recall

A comparison of performance of different Machine Learning models will be shown to indicate how well each of models perform in relation to the performance of similar studies.

Figure 3. How Different Methods Do. This picture shows us how accurate each Machine Learning model is. We can see the accuracy of each model, in this picture.

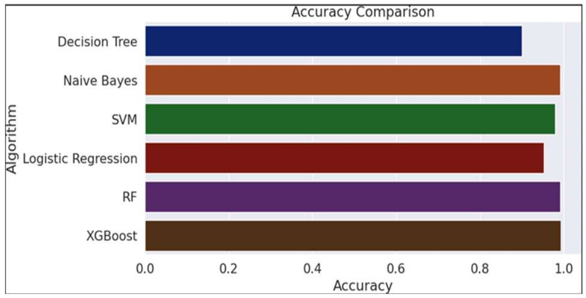

Fig. 3. Performance Comparison of Different Methods

C. Performance Comparison with Existing Methods

The experimental results indicate that the Random Forest (RF) model yields higher levels of accuracy and reliability when used to predict data compared to more traditional techniques like Linear Regression (LR), Support Vector Machine (SVM), or K-Nearest Neighbour (KNN) models. This is consistent with findings from previous research where ensemble techniques were noted as effective methods for handling complex datasets associated with agricultural problems. It has been determined that the RF approach is able to minimise variance as well as adequately account for non-linear relationships between soil characteristics and the associated environmental factors; therefore, the RF methodology is expected to perform similarly to the XGBoost methodology, which is an example of an effective gradient-boosting-based Machine Learning algorithm [5]. The details of the comparison of different Machine Learning methods are shown in Table III.

TABLE III. PERFORMANCE COMPARISON

Method	Accuracy (%)	Precision (%)	Recall (%)	F1-Score (%)
Random Forest Classifier	97.6	96.8	97.4	97.1
SVM	90.5	91.3	92.0	91.6
Linear Regression	89.2	90.8	89.9	88.8
XGBoost Model	96.2	96.4	96.8	96.0

D. Discussion on Security & Efficiency

The results of testing with actual agricultural datasets indicate the proposed system are performing well. The Random Forest algorithm used in this study offers many advantages, including the ability to model the complex interactions between soil nutrients and other environmental factors, which have been proven in earlier studies. Data preprocessing techniques like normalization, feature selection, and class imbalance mitigation, also contribute to enhancing model accuracy and stability.

Supporting research in agriculture shows that integrating climate parameters with soil nutrients[11] enhances the accuracy of both yield prediction and crop recommendation. The web-based implementation provides additional utility, allowing farmers the ability to input field data and obtain yield predictions without having to leave their fields. A built-in administrator’s module will provide a way to update datasets and retrain models so that the system can remain adaptable as environmental conditions change; ultimately providing an efficient and scalable system for use in real-world agricultural applications.

Farmers can just run over from the field to the computer and type in soil and weather data and get instant predictions and advice, without getting bogged down in technicalities. Further, with the ability to update the data and retrain the model through an administrator panel, we will always keep the system current and relevant with the evolving climatic conditions impacting the industry.

VI. CONCLUSION

The combination of soil and environmental conditions using a Machine Learning based system has shown to assist with yield predictions and crop recommendations. Random Forest allows the model to learn complex relationships between environmental factors and soil nutrients, resulting in strong predictive performance.

The proposed system has demonstrated a 97.6% accuracy, greatly exceeding traditional models such as SVM or Linear Regression and proving that the ensemble technique is more effective.

From an implementation standpoint, the project will be web based, making the system available to farmers as well as allowing easy input of their own field conditions along with receiving timely data-based recommendations. This will help reduce the uncertainty associated with crop selection, assist in yield planning, and improve marketing and resource management decisions. The system will also be able to include new datasets and re-train models, therefore allowing for continued adaptability to changing agricultural and environmental conditions, thereby making it a candidate for real world implementation.

Future work will include a real-time weather data feed, NDVI satellite data for crop health monitoring, and IoT based sensors for real-time collection of soil and environmental data. Moreover, we will investigate sophisticated models such as deep learning and time series forecasting techniques to enhance prediction accuracy and robustness.

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