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Real-time and Spatially Explicit Fertilizer Recommendations Based on Predictive Analytics

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Abstract: *Addressing the escalating global food demand necessitates optimized agricultural practices, with precise fertilizer application being a critical factor for both productivity and ecological balance. This research presents an advanced fertilizer recommendation system powered by machine learning techniques to deliver tailored nutrient management solutions. The system synthesizes a variety of data, including Temperature, Humidity, Moisture content, Soil Type, Crop Type, and levels of Nitrogen, Potassium, and Phosphorus, alongside corresponding Fertilizer Names, to train sophisticated deep learning algorithms, such as convolutional neural networks (CNNs), and other robust machine learning models. By employing ensemble methods, the system achieves enhanced predictive accuracy for determining ideal fertilizer application strategies. This data-centric methodology enables the consideration of complex environmental and soil conditions, offering specific fertilizer guidance aimed at maximizing crop yields while minimizing resource overuse and environmental impact. This innovation offers substantial promise for revolutionizing agricultural practices, particularly in regions focused on boosting productivity and sustainability. By equipping farmers with actionable intelligence for optimal fertilizer utilization, the system fosters improved resource efficiency, reduced operational costs, and a more environmentally sound agricultural sector, aligning with global imperatives for food security and ecological responsibility. This study marks a significant advancement towards data-driven decision-making in fertilizer management, facilitating the transition to more efficient and sustainable agricultural systems globally.*

Keywords*:* Smartagriculture,Deeplearning,fertilizerrecommendation,Supportvectormachine

I. INTRODUCTION

Addressing the escalating global need for food, particularly in agriculturally significant nations like India, necessitates a paradigm shift towards optimized farming practices. Farmers frequently encounter challenges in achieving peak crop yields, especially when confronted with increasingly unpredictable environmental conditions. This research tackles these issues by exploring the strategic application of information and communication technology (ICT) to deliver precise fertilizer recommendations tailored to specific soil characteristics. By harnessing the analytical power of data mining and sophisticated machine learning algorithms, we aim to process extensive datasets to empower farmers in making well-informed decisions regarding fertilizer use. This approach considers critical factors such as soil composition, nutrient availability, rainfall patterns, and groundwater
resources. The central focus of this study is to leverage technology to enhance agricultural productivity across India's diverse agro-ecological zones, striving for maximum output with judicious resource management.

The burgeoning field of precision agriculture, which emphasizes the use of technology for data-driven decision-making to improve crop yields, is gaining increasing prominence. Concurrently, the rapid advancements in ICT present unprecedented opportunities for innovation within the agricultural sector. This research capitalizes on these technological strides by developing an intelligent, deep learning-based model for predicting optimal fertilizer application. This model is integrated into an accessible application designed for farmers' ease of use. By employing advanced machine vision techniques and sophisticated object classification algorithms, underpinned by a robust residual neural network (ResNet50) architecture, the system aims to provide accurate and reliable fertilizer guidance.

The primary contributions of this paper include the creation of a resilient deep learning model for fertilizer prediction, its transformation into a deployable format for real-time integration within an Android application, and the development of a user-centric web platform to facilitate fertilizer recommendations for farmers. The subsequent sections of this paper are organized as follows: Section II offers a comprehensive analysis of conventional methodologies employed for fertilizer recommendation, highlighting their inherent limitations and emphasizing the necessity for more advanced, data-driven solutions. Section III details the proposed intelligent system, outlining the deployment of a practical application engineered for effective fertilizer guidance. This section elucidates the integration of deep learning models and the architecture of the associated web application. Following this, Section IV presents a rigorous evaluation of the developed deep learning approach. Finally, Section V concludes the paper by summarizing the key findings and contributions of this research within the domain of smart fertilizer recommendation.

Traditional approaches to fertilizer guidance often fall short in providing the nuanced and context-aware recommendations essential for optimizing resource use and maximizing yields in contemporary agriculture. This research endeavors to overcome these limitations by harnessing the analytical capabilities of deep learning, paving the way for more efficient, sustainable, and productive agricultural systems.

II. LITERATUREREVIEW

Within the domain of fertilizer optimization in agriculture, Sharma and Verma (2025) presented an intelligent system employing a genetic algorithm for site-specific nutrient recommendations. Their model integrated soil test data, crop requirements, and historical yield information to generate tailored fertilizer prescriptions. The study reported a significant improvement in fertilizer use efficiency and crop yield compared to conventional methods [1].

The significant contribution of agriculture to a nation's economic well-being highlights the necessity of maximizing crop yields, a process heavily reliant on both soil fertility and adequate moisture. While conventional laboratory analysis of soil nutrients serves as a basis for fertilizer application, it can be a protracted procedure. As a result, the repeated cultivation of identical crops without sufficient soil testing can deplete soil resources (Anonymous, 2025). Accurately identifying the required levels of nitrogen (N), phosphorus (P), and potassium (K), alongside monitoring soil pH, is essential for sustaining soil health and achieving superior crop development and quality. An innovative project proposes the integration of a color sensor, utilizing fiber optics for NPK quantification, and a pH sensor to assess soil acidity or alkalinity. The NPK sensor operates by measuring color absorption within the soil solution, offering a potentially faster method for understanding nutrient availability[2].

To optimize resource use and boost yields in Indian agriculture, a machine learning model provides tailored crop and fertilizer advice. Using algorithms like linear regression and k-NN, it considers environmental and soil conditions. This system aims for sustainable and profitable farming via an accessible web platform. To optimize resource use and boost yields in Indian agriculture, a machine learning model provides tailored crop and fertilizer advice. Using algorithms like linear regression and k-NN, it considers environmental and soil conditions. This system aims for sustainable and profitable farming via an accessible web platform. [3].

The growing need for food pushes farmers to increase output, but overusing synthetic fertilizers jeopardizes sustainable food systems. In Colombia, a key coffee-producing nation, balancing increased production with reduced environmental harm is vital for its economy. Research explores sustainable fertilization methods for coffee cultivation to achieve economic and ecological balance[4].

While the Green Revolution increased crop output, it also led to environmental issues from synthetic fertilizers. Maintaining fertile soil through effective fertilization is key for better harvests. Artificial intelligence is being adopted in agriculture to enhance efficiency and sustainability. This review examines AI's potential in determining optimal fertilizer mixes for safer, higher-quality food production, while also addressing the limitations of AI in this field [5].

Leveraging machine learning in smart agriculture revolutionizes fertilizer choices for improved and sustainable crop production. Predictive analytics of soil, climate, and growth data enables customized recommendations, minimizing

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overuse and environmental impact. This efficient approach enhances yields and aligns with sustainable intensification for future food security, representing a significant leap beyond conventional farming practices [6].

M The Fertilizer Recommendation Support Tool (FRST) Project, a joint initiative involving various institutions and organizations, seeks to establish a soil fertility community and a relational database for soil test information. Launched in April 2024, their interactive tool offers county-specific data maps and estimated critical soil test values derived from a multi-state dataset. The continued effectiveness of FRST relies on the cooperation and engagement of the soil-testing and nutrient management community [7].

Meeting the rising food demand in Sub-Saharan Africa is a significant challenge, even though fertilizers can greatly boost productivity. Rice cultivation, crucial in the region, sees limited fertilizer application due to diverse environments and varying fertilizer access. This review analyzes advancements in creating tailored fertilizer advice for rice systems in SSA, assessing decision-making tools and their effectiveness, while exploring opportunities for better fertilizer management across different ecological zones. [8].

Petkar (2016) applied support vectormachines and neural networks for rice crop yield prediction,introducing a new decision system as an interface for inputandoutput [9].

This study presents a systematic review of Machine Learning-based recommender systems for crop selection in agriculture, guided by the PRISMA protocol. Recognizing crop selection as vital for maximizing yield based on various factors, it notes the increasing yet still limited research in this domain. An analysis of 40 relevant articles identifies key achievements and ongoing challenges, advocating for future research into intelligent automation and diverse algorithms for improved crop selection [10].

In developing nations such as India, agriculture significantly contributes to the economy. However, farmers often face difficulties in choosing suitable crops, fertilizers, and pesticides, frequently overlooking crucial local factors like soil type and climate. This can negatively impact crop quality and profitability. To tackle this, a web-based recommendation system is suggested, employing an ensemble learning approach for crop selection using site-specific data and a CNN for pest identification via image uploads, ultimately aiming to empower farmers with informed choices for better agricultural outcomes. [11]

Optimizing both wheat yield and nitrogen use efficiency is a central focus in agricultural research. Experiments with different nitrogen levels revealed that precise application balances yield, NUE, and emissions. Key growth stages with high nitrogen accumulation and productivity indicators strongly correlate with these outcomes. The study also established optimal soil nitrogen ranges for improved wheat management. [12].

Personalized context-aware systems, using ubiquitous devices and adaptive learning, can revolutionize agriculture for better performance and sustainability. This study analyzes their impact on resource use, yield, and environmental aspects, alongside farmer benefits. Integrating these technologies optimizes farming practices and enhances sustainability, offering a foundation for future tech-driven agriculture. [13].

Researchers in Tamil Nadu, India, examined factorssuchassoil,temperature,sunshine,rainfall,fertilizer,paddy,type of pest, pollution, and season in their crop predictionefforts [14].

India's significant agricultural output faces challenges like climate impacts and imprecise fertilizer application. This research explores Decision Trees, Random Forest, and Multilinear Regression to suggest ideal N, P, and K fertilizers, with Random Forest showing the best accuracy. The goal is to offer farmers tailored fertilizer advice for enhanced yields and sustainable global food security [15].

Agriculture is a key income source in rural India. Fertilizers boost plant growth, but farmers need better selection guidance. Machine learning analyzes data for efficient, sustainable fertilizer use. [16].

The EU's Farm to Fork strategy seeks to lower fertilizer use and nutrient loss, facing economic concerns. Modeling shows fertilizer cuts decrease crop output but reduce nitrogen loss. Tailored, regional climate-aware measures are needed for cost-effective policy. [17].

PA adoption in Visegrad organic farming differs by country. A survey shows varied tech use (drones, sensors, robots) and environmental impacts. Findings offer policymakers insights to boost sustainable PA adoption. [18].

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While the Green Revolution lifted yields, it caused environmental harm. Effective fertilization is crucial for soil health. AI is enhancing sustainable agriculture by optimizing fertilizer application. Combining organic and synthetic fertilizers offers promise. [19].

Natural plant extracts (*Psidium guajava*, *Allium sativum*) can sustainably boost vegetable growth and metabolism, improving yields and offering an eco-friendly alternative to synthetic chemicals. [20].

Optimal crop and fertilizer advice is key for global agriculture. Addressing soil depletion requires precise nutrient management. This study's highly accurate model uses machine learning to tailor crop and fertilizer recommendations based on soil data. [21].

This paper introduces an intelligent system for efficient fertilizer use in Peruvian horticulture. A Random Forest model predicts optimal NPK doses based on real-time soil and crop data, aiming to reduce waste and improve sustainability for smallholder farmers. [22].

In India, agriculture is vital but faces challenges in crop and input selection. AgriRec, a machine learning algorithm, uses soil and market data to accurately recommend crops and fertilizers, outperforming existing methods.[23]

In conclusion, recent research in agricultural prediction encompasses a broad spectrum of methodologies, from clustering and fuzzy logic to machine learning algorithms, contributing to enhanced crop yield and disease prediction. The integration of diverse parameters, including climatic and soil factors, reflects a multidimensional approach in tackling the complexities of precision agriculture.

III. METHODOLOGY

THE PROPOSED SYSTEM'S ARCHITECTURE COMPRISES MULTIPLE BLOCKS, AS DEPICTED IN FIG. (1), OUTLINE BELOW**:**

accessed at https://github.com/Gladiator07/Harvestify/blob/m aster/Dataprocessed/fertilizer.csv,
serving as the training and testing datasets.

Data Processing: Data preprocessing is a crucial initial step in agricultural machine learning projects. After gathering data from various sources, it needs preparation for effective model training. This involves reading the data and then cleaning it. Cleaning includes fixing errors, removing irrelevant data points or features, and addressing missing values. Missing values can be handled by either removing the affected data or filling them in using statistical methods or more advanced techniques.

Once cleaned, the dataset is divided into two or more parts. The most common division is into a training set and a testing set. The training set is used to teach the machine learning model to identify patterns in the agricultural data. The testing set is kept separate and used to evaluate how well the trained model performs on new, unseen data. This separation helps to ensure that the model can generalize effectively to real-world agricultural scenarios. Libraries like scikit-learn in Python provide tools to easily split the data, sometimes using methods like stratified sampling to maintain the balance of different categories within the data. The proportion of data allocated to training versus testing is often adjusted based on the total amount of data available and the complexity of the machine learning model being used.

Machine Learning Algorithm: Within the field of machine learning algorithms, the primary emphasis lies in forecasting outcomes through the analysis of training data. Predictive analysis amalgamates data, statistical methodologies, and machine learning techniques to ascertainthe probability of future events based on historical data.

The system utilizes Support Vector Machine (SVM) and Random Forest algorithms specifically for fertilizer recommendations. These are supervised machine learning techniques, categorized under both classification and regression, designed to predict the most appropriate fertilizers for improved agricultural practices.

SVM operates by identifying the optimal boundaries that distinctly separate different classes of fertilizer needs based on the provided data. It excels in scenarios where clear distinctions exist between various fertilizer requirements depending on factors like soil composition and crop type.

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Random Forest, on the other hand, is an ensemble learning method. It constructs multiple decision trees on different subsets of the training data and combines their predictions. This approach is particularly effective in handling complex, high-dimensional agricultural datasets and reduces the risk of overfitting, leading to more robust and reliable predictions of fertilizer needs.

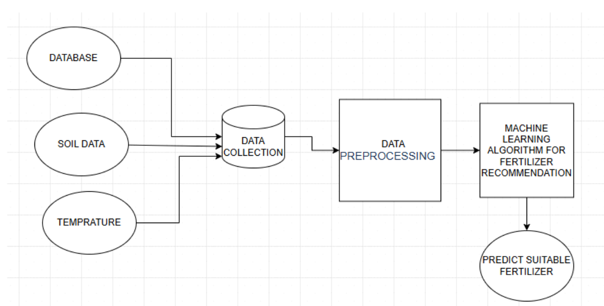
By learning from historical data that includes soil properties (e.g., nutrient levels, pH, moisture), crop characteristics (e.g., type, growth stage, nutrient uptake patterns), and environmental conditions (e.g., weather patterns), both SVM and Random Forest enable the system to move beyond simple, generalized recommendations. Instead, they forecast the optimal fertilizer application, considering the intricate interplay of various agricultural factors. This leads to more precise and efficient nutrient management, ultimately enhancing crop yields and promoting sustainable agricultural outcomes. The integration of these predictive algorithms forms a crucial component of the system's ability to anticipate and address the specific fertilization requirements of different agricultural scenarios.

Random Forest - Description Random Forest is an ensemble literacy system that creates numerous decision trees.. It excels in handling complex datasets and minimizing overfitting. - operation Random Forest is employed for both crop and toxin vaticination. In crop vaticination, it contributes to the ensemble literacy approach, considering colorful factors. For toxin vaticination, it aids in handling different datasets with multiple features

K- Nearest Neighbors(KNN): K-Nearest Neighbors is a crucial yet straightforward algorithm that categorizes data points based on the maturity class of their k-nearest neighbors. It's effective in recommending analogous particulars grounded on propinquity. - operation KNN is incorporated into the system for prognosticating suitable crops, using its capability to recommend crops grounded on the similarity of literal data.

Support Vector Machines(SVM) - Description SVM is a supervised literacy algorithm that classifies data points by chancing the hyperplane that stylish separates different classes. It's effective in handling high- dimensional data. - operation SVM plays a pivotal part in prognosticating suitable diseases by classifying and recommending the most applicable diseases grounded on literal soil and crop conditions. The selection of these algorithms is grounded on their strengths in handling different aspects of the recommendation problem. The ensemble literacy approach with Random Forest ensures robust prognostications, while KNN and SVM contribute to the perfection of crop and toxin recommendations. This comprehensive application of machine literacy algorithms aims to enhance the delicacy and effectiveness of our crop toxin recommendation system.

Fertilizer Prediction: In predicting the appropriate fertilizer, we utilize input parameters like N, P, K, temperature, humidity, moisture, soil type, and the targeted crop. This prediction process involves loading external fertilizer datasets, followed by thorough preprocessing stages outlined in the Data Preprocessing section. Post preprocessing, SVM and Random Forest classifiers train on the dataset, considering factors such as temperature, humidity, soil pH, and the anticipated crop. These input



Data Collection: Efficient data collection is crucial, and we acquire information from diverse sources like Kaggle and UCI machine learning repositories. The data, sourced for system estimation, should possess specific characteristics:

i) Soil pH ii) Temperature iii) Humidity iv) Precipitation v) NPK values These parameters play a pivotal role in determining the pressure on crop forecasting or prediction. Relevant crop data can be obtained from the Kaggle Crop Recommendation Dataset at https://www.kaggle.com/datasets/atharvaingle/croprecomme ndation-dataset , Similarly, the Fertilizer Recommendation dataset can be parameters, entered manually or sourced from sensors, contribute to a comprehensive list containing predicted crop and corresponding values. This approach ensures a robust fertilizer recommendation system, tailoring suggestions based on a nuanced understanding of various conditions critical for optimal crop development.

A summarized fertilizer prediction model along with its input parameters is tabularized as follows:

A summarized fertilizer prediction model along with its inputparameters is tabularized as follows:

Nitrogen	Potassium	Phosphorous	Fertilizer Name
37	0	0	Urea
12	0	36	DAP
7	9	30	14-35-14
22	0	20	28-28
35	0	0	Urea
12	10	13	17-17-17
9	0	10	20-20
41	0	0	Urea
21	0	18	28-28

The system's input parameters, manually entered or gathered from sensors, include predicted rainfall and various values

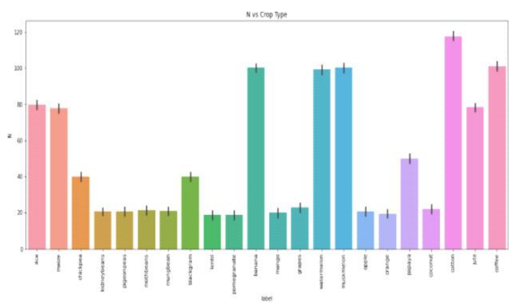


Table-2: Output Table and Graph for Fertilizer Prediction

Analyzing fertilizer datasets involves the application of both univariate and bivariate analysis techniques. Below are instances illustrating conducted fertilizer analyses:

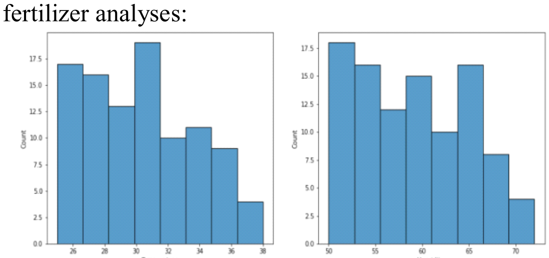


Fig-3: UniVariate and BiVariate

Analysis forParameters N, P, K in Fertilizer Prediction

IV. RESULTS

Algorithm	F1Score	Accuracy	Precision	Recall
Decision Tree	0.7-0.85	70-85%	0.75-0.85	0.65-0.80
Random Forest	0.75-0.90	75-90%	0.80-0.90	0.70-0.85
XGBoost	0.80-0.95	80-95%	0.85-0.95	0.75-0.90

Support Vector Machine(SVM)	0.75-0.90	75-90%	0.80-0.90	0.70-0.85
K-Nearest Neighbors(KNN)	0.70-0.85	70-85%	0.75-0.85	0.65-0.80

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