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Review - A Machine Learning-Based Fertilizer Recommendation System for Sustainable Crop Yield

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Abstract - *One of the biggest producers of agricultural goods in the world, India is well known for its textiles, dry fruits, grains, fish, eggs, coconut, sugarcane, and a variety of vegetables. Despite this achievement, large number of Indian farmers continue to cultivate the same crops without considering crop diversification and rotation. Furthermore, overuse of fertilizers, frequently without proper dose understanding, damages long-term production by degrading soil and creating a nitrogen imbalance. We created a machine learning-based recommendation system that makes recommendations for the best crops and fertilizers depending on soil and weather conditions in order to address these problems. This method maximizes productivity while maintaining soil health, allowing for sustainable farming. Through improved crop planning and nutrient management, this approach boosts farmers' profits, promoting environmental sustainability and economic resilience in Indian agriculture.*

Key Words: Fertilizer recommendation, Machine learning, Sustainable agriculture, Crop yield optimization, Soil health management.

1. INTRODUCTION

Global fertilizer consumption is expected to grow by 2% in FY 2024 to 195.4 Mt. Consumption of N is forecast to increase by 2% to 111.6 Mt, consumption of P2O5 by 2% to 47.1 Mt, and consumption of K2O by 3% to 36.7 Mt. Fertilizer Recommendation Systems (FRS) as shown in figure 2 are vital instruments in contemporary agriculture, providing customized advice on the kind, amount, and technique of fertilizer application according to particular crop and soil requirements. Through the integration of information on soil characteristics, crop needs, and environmental circumstances, FRS facilitates more accurate fertilizer application, which directly supports soil health and sustained crop productivity as showed in figure 1. These systems are becoming more and more important since they minimize farmers' financial burden by assisting them in optimizing fertilizer costs while simultaneously enhancing crop production and quality. By reducing environmental hazards like greenhouse gas emissions, groundwater contamination, and fertilizer runoff, FRS promotes more sustainable farming methods and meets the pressing demand for more food production to feed the world's expanding population.

Fig.1: Fertilizer composition to crops

Notwithstanding its benefits, FRS carries number of hazards that should be carefully considered. Relying too much on general guidelines can result in an imbalance of soil nutrients, which could endanger long-term fertility by causing nutrient deficits or toxic accumulation in the soil. Furthermore, the efficacy of FRS is largely dependent on having access to reliable data and technological infrastructure, which presents a challenge in rural areas with scarce resources. The upfront costs associated with soil testing and data collection may also put small-scale farmers at risk financially, thereby restricting the technology's availability. Furthermore, environmental problems like eutrophication—a dangerous surplus of nutrients in water bodies—can arise and affect local ecosystems if suggestions are misapplied because of inaccurate data or misinterpretation. Studies indexed in Scopes and research from Crop World over the past five years show a distinct trend towards precision agriculture, where data-driven FRS are being used more and more to improve crop management techniques. Adoption rates have increased dramatically worldwide, especially in areas like Asia and Africa where agriculture is the main source of income.

Recent developments in satellite monitoring, IoT-based soil sensors, and mobile applications for FRS are in line with this change, as they offer real-time data for more precise suggestions. Another growing area of study is the integration of machine learning with FRS, which has promise for increasing prediction accuracy. The expansion in FRS use over the last five years is illustrated graphically, which also shows a favorable trend in increased crop yields when comparing FRS-based techniques with traditional approaches. Furthermore, studies show that FRS recommendations significantly lessen environmental effect, including lower runoff of phosphorus and nitrogen. Adoption rate graphs, comparison visuals of the effects of nutrient runoff, and conceptual diagrams of FRS inputs and outputs can all be used to graphically support these findings and show how well the system promotes sustainable agriculture.

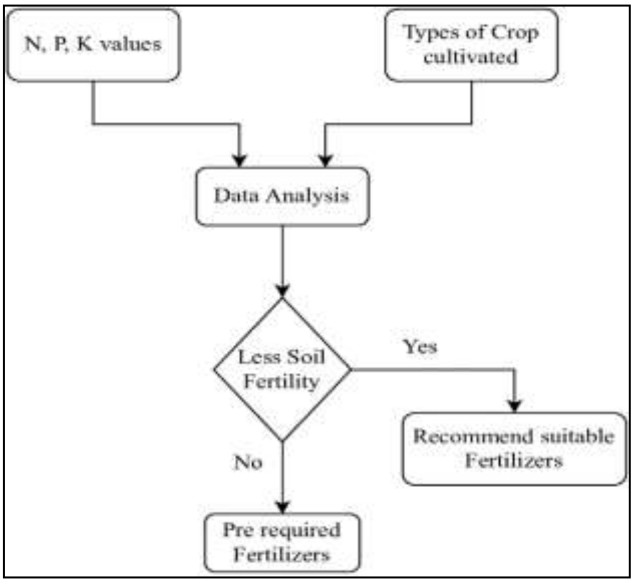

Fig.2: Fertilizer Recommendation System

2. LITERATURE SURVEY

This review of the literature looks at new developments in fertilizer recommendation systems that maximize soil health and crop productivity. It emphasizes efficient methods and their effects by examining a variety of approaches, such as site-specific nutrient management and deep learning models. In order to improve agricultural sustainability, the survey highlights the necessity of accurate, data-driven solutions given in table1.

Passandideh et al. [1] evaluated phosphorus fertilizer needs in Iran, considering environmental risks. They found not all soils required phosphorus, and improper application could reduce yields. However, careful use may help reduce soil erosion, supporting balanced phosphorus use for environmental health. Dupré et al. [2] created a boron recommendation system for Quebec's acidic and neutral soils using machine learning, which improved boron management and helped farmers make crop-specific fertilizer decisions for better yields and lower environmental impact. Ichami et al. [3] studied nitrogen efficiency in African maize fields, revealing regional variations in response to fertilizers. Key factors like rainfall and nitrogen availability were identified, emphasizing the need for location-specific fertilizer guidance to improve yield. Oliveira et al. [4] developed a nutrient recommendation for cabbage using nitrogen, phosphorus, and potassium, helping farmers optimize fertilizer use to boost yield and soil health.

Wako et al. [5] investigated balanced fertilizers on Ethiopian sorghum. They used soil maps to identify optimal mixes, notably NPSZn, enhancing productivity and showing the potential for nutrient mapping in specific crops and regions. Hatta et al. [6] recommended phosphorus and potassium for Indonesian paddy fields, focusing on location-specific fertilizer doses to prevent overuse. The study, however, did not address other nutrients. Jiang et al. [7] examined nitrogen rates in Northeast China's maize fields, identifying optimal nitrogen applications to boost productivity and reduce environmental damage, though it only considered nitrogen, not other nutrients. Hossain et al. [8] introduced the Online Fertilizer Recommendation System in Bangladesh, improving yields with tailored recommendations based on soil and crop type, though it lacks machine learning for further refinement. Oliveira et al. [9] studied balanced nutrient use in potatoes in Brazil, highlighting the importance of soil condition considerations in fertilizer applications to avoid nutrient imbalance.

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Montanez et al. [10] developed a prototype using image processing to assess soil nutrients and recommend fertilizers quickly. Despite struggles with nitrogen detection, it showed potential for efficient soil management. Chabi et al. [11] focused on optimal fertilizer doses for soybean in Benin, showing that certain nutrient combinations almost doubled yields, providing guidance on customized fertilizer use. Mumbach et al. [12] refined phosphorus recommendations for Southern Brazilian soils, particularly clay-rich ones. Although higher phosphorus requirements can increase costs, this approach supports efficient phosphorus use. Nataraja et al. [13] found that using bio fertilizers with standard nutrients improved paddy productivity. However, the study's narrow focus may limit its broader applicability. Admasu et al. [14] validated soil maps in Ethiopia for wheat production, finding mixed results for multi-nutrient fertilizers, which suggest a need for more location-specific testing.

Kassa et al. [15] used the QUEFTS model to recommend fertilizers for Ethiopian barley, showing it accurately predicted nutrient needs. However, this model might not be as effective outside the specific crop and region.
Raut et al. [16] combined machine learning and IoT for crop-fertilizer recommendations, using Random Forest for high prediction accuracy on key soil parameters, improving farmer decisions. Upadhyaya et al. [17] used machine learning, like XGBoost and LSTM, for high-accuracy fertilizer recommendations, providing insights to refine agricultural technology. Pandit et al. [18] created a system using IoT and Light Boost for crop-fertilizer recommendations, benefiting Indian farmers with real-time soil data. Keerthi et al. [19] tested machine learning for crop-fertilizer suggestions, noting high accuracy with XGBoost and Decision Tree, though facing complexity issues. Sharma et al. [20] used machine learning to recommend crops based on soil, climate, and water, supporting efficient resource use.

Bondre and Mahagaonkar [21] used machine learning to predict crop yields and recommend fertilizers, helping farmers optimize resources based on historical data. Melasagare's et al [22] study demonstrates how employing algorithms such as regression and classification can increase crop output, lower fertilizer consumption, and support sustainable farming methods.

Table -1: Summary and Methodology

Author	Datasets	Feature extraction	Algorithms	Results
Passandideh et al [1]	Soil samples and field tests on maize crops across 90 farms	Soil total phosphorus (P), Environmental P Index (EPI), yield response	EPI-based phosphorus management model	The recommended P dosage significantly decreased soil erosion, but EPI found that no P fertilizer resulted in a 23% yield decline.
Dupré et al. [2]	365 soil samples from Québec, Canada for boron analysis	Soil properties (pH, organic carbon, Ca, Mg), Boron levels (BHW and BM3), crop requirements	AutoML with supervised learning	Generated a boron classification model with R2 values between 0.36 and 0.99 for different soil parameters; the boron recommendation model had an R2 value of 0.63

				for crop-specific requirements.
Stephen M. Ichami, et al. [3]	On-farm data from Kenya and Sub-Saharan Africa	Fertilizer response (FR), nitrogen use efficiency (N-AE), soil data	Meta-analysis, Linear regression	High levels of variability in fertilizer reaction were discovered, highlighting the need of soil and climate conditions for improving recommendations.
Thaísa, et al. [4]	Cabbage fertilizer experiments	Crop demand, nutrient recovery efficiency, soil nutrient supply	Nutritional balance model	Appropriate fertilizer suggestion for cabbage based on soil nutrient availability and crop needs.
Wako, A. et al. [5]	Crop yield data from local fields	Nutrient composition and yield data	Regression algorithms	Predictions of crop yield were made with a high degree of accuracy, and recommendations for soil tests were helpful.
Hatta, R. et al. [6]	Experimental paddy fields	Soil quality indicators, crop requirements	Decision trees, Neural networks	Maximized agricultural output by the usage of fertilizer based on soil investigations.
Jiang, W. et al [7]	Various published datasets	Soil parameters, crop yield data	Machine Learning models	Increased precision in fertilizer recommendations with the use of machine learning techniques.
Hossain, M.A. et al [8]	National soil database	Soil test values	Statistical analysis	Yield increase of 7–22% while utilizing the prescribed fertilizer dosages.
Oliveira, R.C. et al [9]	Field experiments in Brazil	Leaf nutrient analysis	Linear mixed-effect model	Higher potato yields are the result of proper nutritional balance.
Montañez et al [10]	Soil samples from tests	Soil pH, N, P, K levels	Image processing techniques	The prototype successfully recognized soil variables and made recommendations.
Faki O. Chabi et al. [11]	Soybean field trials (2018-2019)	Soil nutrient levels (N, P, K, Mg, Zn)	Response surface methodology	The application of ideal fertilizer dosages significantly increased soybean output.

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Mumbach et al [12]	Soil samples from agricultural plots.	Extracted soil nutrient levels, moisture, pH	Regression analysis, statistical modeling	enhanced agricultural yields by determining the best fertilizer types and application rates.
Nataraj et al [13]	Crop production data from regional farms	Soil quality indicators, crop yield measurements	Decision Tree, Random Forest	obtained precise fertilizer recommendations, which enhanced soil output and health.
Almaz Admasu et al [14]	Soil and crop data from different Ethiopian farms	Nutrient content, soil texture	SVM, k-NN	gave specific crop advice and noted a notable increase in crop production.
Kassa et al. [15]	Field data from barley crops in Wolaita Zone, Ethiopia	Nutrient levels of N, P, and K	QUEFTS model	Accurate nutrient recommendations improved site-specific barley output by correlating with actual yield.
Raut, A., et al [16]	Soil data collected through IoT sensors, including factors like NPK values, humidity, temperature, and rainfall	Extraction of soil parameters (NPK values) and environmental factors (temperature, humidity, rainfall)	Random Forest	High accuracy in crop and fertilizer recommendations.
Upadhyaya et al [17]	Various agricultural datasets with soil characteristics, NPK values, and field data	Data processed to calculate error metrics (MSE, MAE) for comparing model performance	KNN, SVM, Random Forest, XGBoost, LSTM	The LSTM measurements revealed a MAE of 0.0651 and an MSE of 0.0085.
Pandit, A., et al [18]	Soil and crop data collected through IoT sensors, including NPK levels, soil types, and regional characteristics	Sensor data on soil parameters and environmental factors were extracted to identify suitable crops and fertilizers	Light Boost	System dependability is impacted by the precision of sensor data, which varies by area.
Keerthi, H., et al [19]	Soil and crop data, environmental conditions	Extraction of soil nutrients, crop and weather data	XGBoost, Decision Tree, AdaBoost, SVM, Random Forest	The most accurate algorithm was the Decision Tree algorithm.

Ram Sharma et al. [20]	Soil and weather data along with crop yield data	Soil nutrient content, crop type, weather conditions	Gradient Boosting Machine algorithm	86.5% prediction accuracy was attained for the ideal fertilizer type and quantity.
Bondre, D.A., Mahagaonka. S. [21]	Crop yield data, soil nutrient values, historical agricultural data	Soil nutrient analysis, crop yield history	Support Vector machine Random Forest	Accurate fertilizer recommendations and efficient output forecasting
S. M. Melasagare,et al [22]	agricultural datasets	soil pH, temperature, rainfall, nitrogen, phosphorus, potassium levels, and crop type	linear regression, decision trees, and random forests	Improved efficiency in fertilizer use, enhanced crop yield, and environmental sustainability.

3. CONCLUSIONS AND FUTURESCOPE

The significance of sophisticated techniques in crop yield prediction and nutrient recommendation systems for sustainable agriculture is highlighted by research conducted between 2019 and 2024. Research has demonstrated that the application of data-driven decision support systems, machine learning, and the Internet of Things can greatly improve the precision of crop suitability forecasts and fertilizer recommendations. These methods assist farmers in making well-informed decisions, which eventually increases output and lessens environmental effects by maximizing nutrient utilization. In addition, nutrient recommendation models—such as those for nitrogen, phosphorus, and other vital nutrients—are increasingly taking soil characteristics, crop-specific nutrient requirements, and environmental risk indices into account in order to produce more accurate and long-lasting solutions. But issues still exist with soil and climate variability, as well as a lack of data for certain crops or geographical areas.

More resilient and flexible recommendation models that consider localized data for different soil types, crop varieties, and environmental circumstances should be the main goal of future research. The precision and dependability of suggestions could be further enhanced by increasing the use of hybrid models, which blend knowledge-based and data-driven methodologies. Furthermore, cutting-edge machine learning algorithms combined with real-time IoT data may allow for dynamic modifications to nutritional recommendations according to the state of the field. Scalable solutions for smallholder farmers in underdeveloped nations, where resources and data may be scarce, should also be investigated in research. Finally, a stronger focus on interdisciplinary cooperation may result in more all-encompassing systems that consider ecological and agronomic factors, promoting sustainable farming methods globally.

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