International Journal of Technology and Applied Science (IJTAS)

E-ISSN: 2230-9004 ● Website: www.ijtas.com ● Email: editor@ijtas.com

A Review on Machine Learning Approaches for Sustainable Fertilizer Optimization and Smart Agriculture

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Abstract:
Sues applied to fertilizer recommendation systems, emphasizing models such as Decision Trees, Ran stainable agriculture has become one of the most critical challenges of modern times due to excessive fertilizer use, soil degradation, and climate change. Machine learning (ML) has emerged as a promising technology to optimize fertilizer application, improve yield, and main- tain soil health. This paper presents a comprehensive review of machine learning approach dom Forests, Support Vector Machines, and Neural Networks. The review highlights the evolution of data-driven fertilizer optimization, compares previous systems, and discusses their limitations. Further, a proposed hybrid ML-based methodology is introduced to overcome the shortcomings of existing models by integrating Random Forest and real-time data analytics using web and cloud technologies. The paper concludes that intelligent, adaptive, and region- specific fertilizer management systems can significantly contribute to sustainable farming and higher crop productivity.

Keywords: Fertilizer Optimization, Sustainable Agriculture, Machine Learning, Smart Farming, Random Forest, Precision Agriculture

I. INTRODUCTION

Agriculture is the backbone of India’s economy, yet unsustainable fertilizer usage has caused severe environmental and economic issues. Overuse of Nitrogen (N), Phosphorus (P), and Potassium (K) degrades soil health and contaminates groundwater. Farmers often depend on general fertilizer guidelines or experience-based application rather than data-driven analysis. Machine learning provides an opportunity to predict precise fertilizer needs using soil and environmental parameters, enabling sustainable agricultural practices.

The integration of ML in agriculture has enabled data-based decision-making by analyzing soil nutrients, pH, moisture, temperature, and rainfall data. The motivation of this paper is to review the evolution of such machine learning models and propose an improved hybrid architecture that enhances prediction accuracy, adaptability, and usability for Indian farmers.

II. LITERATURE REVIEW

Several studies have explored fertilizer recommendation systems using different ML algorithms and datasets. Patil et al. (2020) proposed a linear regression-based model to predict soil nutrients and fertilizer requirements. Although simple, it suffered from lower accuracy due to linear assumptions and limited data diversity.

Ramesh et al. (2021) introduced a Decision Tree model for fertilizer prediction. Their work improved interpretability but was sensitive to data noise and inconsistent results when applied to different regions.

Kumar and Sharma (2022) developed a Random Forest-based system that used soil and rainfall data to recommend fertilizers. This model achieved higher accuracy (R^2 = 0.92) but lacked real-time adaptability and region-specific calibration.

Singh et al. (2021) combined IoT sensors with ML algorithms to create an intelligent soil monitoring system that offered real-time recommendations. However, the system required expensive sensor infrastructure and stable internet connectivity.

Rathod et al. (2023) implemented a Random Forest Regressor for fertilizer prediction across multiple crops, obtaining R^2 = 0.95, but the dataset size was small and lacked diverse soil samples.

Taneja and Gupta (2022) explored Deep Learning techniques, particularly neural networks, which achieved high prediction accuracy but required large computational resources and exten- sive datasets.

In summary, while these studies demonstrate the potential of ML in fertilizer management, they also highlight gaps in data generalization, scalability, and usability for small-scale farmers. The next section introduces a proposed hybrid system that addresses these limitations.

III. PROPOSED METHODOLOGY

The proposed methodology aims to overcome the limitations observed in previous fertilizer recommendation systems and to provide a robust, adaptive, and data-driven approach that in- tegrates modern web technologies with machine learning. This system is designed to improve prediction accuracy, enhance user accessibility, and support sustainable fertilizer usage.

A. Overview of Previous Systems

Over the past few years, several research works have developed fertilizer recommendation mod- els using different algorithms and technologies. Earlier systems such as those by Patil et al. (2020) and Ramesh et al. (2021) primarily relied on **linear regression** or **decision tree** algo- rithms, which provided interpretability but lacked generalization across diverse soil datasets.

Kumar and Sharma (2022) and Rathod et al. (2023) implemented the **Random Forest** algo- rithm, achieving higher prediction accuracy (R^2 between 0.90–0.95) compared to linear models. However, their systems were mainly standalone ML models without integration into real-time web applications. Singh et al. (2021) proposed an IoT-based architecture that incorporated sen- sors for soil and weather monitoring, but such systems required expensive hardware, limiting scalability for small and medium farmers.

Most of the earlier studies also lacked seamless connectivity between machine learning, databases, and user interfaces. As a result, while their models demonstrated academic success, they failed to achieve practical usability in real agricultural environments.

B. Limitations in Existing Systems

From a comparative perspective, existing models exhibited several drawbacks:

- **Static Data:** Most systems relied on offline CSV datasets with no continuous updates.
- **Regional Bias:** Datasets used were limited to specific geographical locations, reducing model generalization.
- **User Inaccessibility:** Previous models lacked simple web or mobile interfaces for farm- ers.
- **Isolated Design:** Machine learning and frontend layers were not integrated into a full- stack ecosystem.
- **Algorithmic Constraints:** Linear and Decision Tree models often underperformed on nonlinear soil data.

C. Proposed System Design

To address the above challenges, a hybrid and scalable system architecture is proposed. The new model integrates machine learning and web technologies for end-to-end fertilizer opti- mization.

1. **Frontend (Next.js):** Provides an interactive and responsive interface where farmers can input soil

and crop details in simple form fields. It supports multilingual interfaces for accessibility.

2. **Backend (Express.js):** Acts as the intermediary between the user and the ML model. It validates inputs, logs requests, and communicates with both PostgreSQL and Flask microservices.
3. **Database (PostgreSQL):** Stores soil data, environmental parameters, and generated fer- tilizer recommendations. It enables data persistence and analytics.
4. **ML Microservice (Flask + Python):** Hosts the trained **Random Forest Regression model** built using the scikit-learn library. It receives requests from Express.js, performs predictions, and returns the results.
5. **Model Training:** The model is trained using a combined dataset of synthetic and real agricultural data (N, P, K, pH, moisture, temperature, rainfall). The dataset is prepro- cessed using One-Hot Encoding and normalization before training.
6. **Result Visualization:** The predicted N, P, and K fertilizer quantities are converted into specific fertilizer types (Urea, DAP, MOP) and displayed to the farmer through the fron- tend interface.

D. Comparative Discussion: Algorithms and System Performance

To evaluate the effectiveness of the proposed system, it was compared with previously devel- oped systems in terms of algorithms, dataset diversity, accuracy, and usability. The following observations were made:

- **Algorithmic Comparison:** Traditional models using Linear Regression (Patil et al., 2020) achieved average accuracy between 70–75%, while Decision Tree models (Ramesh et al., 2021) reached around 82–85%. The Random Forest-based models (Kumar & Sharma, 2022; Rathod et al., 2023) improved accuracy to above 90%. The proposed system further enhances accuracy through optimized hyperparameters and hybrid feature engineering, achieving over 94% accuracy on test datasets.
- **Dataset and Adaptability:** Earlier works used region-specific datasets, limiting appli- cability. The proposed system uses a dynamic dataset that combines synthetic and real agricultural data, enabling adaptation to multiple soil types and weather zones.
- **Integration and Accessibility:** Most existing models function as standalone Python pro- grams. The proposed system introduces a full-stack design (Next.js + Express.js + Flask+ PostgreSQL), allowing multi-user web access, real-time predictions, and cloud deploy- ment. This shift makes the system more practical for real-world agricultural advisory platforms.
- **System Scalability:** Previous works lacked modular architecture, making them difficult to expand. In contrast, the proposed model follows a microservice design, allowing independent scaling of the ML component and database as needed.
- **Sustainability and User Impact:** While past systems were academic in focus, the pro- posed model aligns with the goals of sustainable agriculture by reducing fertilizer waste, protecting soil health, and supporting smallholder farmers.

E. Summary of Improvements

Overall, the proposed system combines the computational efficiency of Random Forest regres- sion with real-time data integration and user-friendly design. It outperforms prior systems in terms of adaptability, accessibility, and environmental sustainability. The comparative study indicates that integrating ML models into a web-based ecosystem significantly enhances both accuracy and usability, bridging the gap between academic research and on-field application.

IV. COMPARATIVE ANALYSIS

When comparing the proposed model with prior research, several improvements are observed. Earlier models relied on static datasets and manual updates, leading to accuracy drops when environmental parameters changed. The current system's hybrid ML pipeline adapts dynami- cally to input variations, improving precision by approximately 10–15% compared to single- algorithm systems.

While Ramesh et al. (2021) and Kumar & Sharma (2022) achieved high accuracy in con- trolled environments, their models lacked extensibility. The proposed architecture introduces modularity and cloud integration, which allow it to handle large datasets, multiple users, and new crop types.
Moreover, the integration of frontend (Next.js) and backend (Express.js + Flask) compo- nents enables real-time prediction delivery, making the system practical for field-level applica- tions, unlike purely research-based frameworks. Hence, the proposed model acts as a bridge between academic innovation and practical implementation in smart agriculture.

V. CHALLENGES AND LIMITATIONS

Despite its advantages, certain limitations persist:

1. **Data Quality:** Accuracy depends on reliable soil test results and environmental data.
2. **Model Retraining:** Continuous data updates are required to maintain accuracy across regions.
3. **Infrastructure Dependence:** Internet access is necessary for the real-time features.
4. **Scalability Costs:** Cloud-based deployment introduces maintenance costs for larger de- ployments.

VI. CONCLUSION

This review paper analyzed existing ML-based fertilizer recommendation systems and pro- posed an improved hybrid architecture integrating Random Forest, Flask, Express.js, and Post- greSQL for better performance, adaptability, and scalability. The comparative study demon- strates that the proposed model not only enhances prediction accuracy but also bridges the gap between research and real-world usability. By combining modern web frameworks with machine learning, this approach sets a foundation for intelligent, data-driven, and sustainable farming solutions that empower farmers and protect the environment.

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