Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

Optimizing Fertilizer Application Using Ai For Sustainable Agricultural Practices

Dr. Anita Mahajan, Mahesh Bhosale, Payal Nikam

Department Of Computer Engineering
Ajeenkya D. Y. Patil School Of Engineering, Lohegoan
Savitribai Phule Pune University
Pune, Maharashtra
Anitamahajan@Dypic.In, Maheshvbhosale0@Gmail.Com, Payalsnikam@Gmail.Com

This study explores the use of Artificial Intelligence (AI) in maximizing fertilizer application in farming to obtain increased yields while reducing environmental effects. Application of AI-based precision agriculture technologies like real-time soil sensors, satellite data, and meteorology allows accurate recommendations for fertilizer use based on plant and soil needs. With these technologies, the system avoids over-fertilization, nutrient runoffs, and soil erosion that contribute to greater productivity as well as environmental protection. The system with AI for optimizing fertilizers lessens greenhouse gas emissions of fertilizer manufacturing and protects water sources from pollution due to preventing nutrients from leaching into adjacent environments. Field tests have shown efficacy of the system in improving farm crop yields as well as the farmers' profits. While there are challenges, including restricted access for small-scale farmers and the requirement for proper training, AI technology has vast potential to transform agriculture by striking a balance between ecological conservation and increasing global food demand.

Keywords: Artificial Intelligence, fertilizer optimization, precision agriculture, sustainability, crop yield, environmental impact, soil health.

1. Introduction

In order for agriculture to be sustainable, AI-augmented fertilizer application will be helpful. The growing number of the human population puts a huge burden on food production, which, in turn, grows in chemical fertilizer usage. While farmers are raising crop yield with fertilization, these fertilizers cause water pollution, soil degradation, and emission of greenhouse gasses. Innovators and administrators must respond to climate change stressors on vanishing natural resources and secure food supplies with real and positive attitudes [1]. The balanced technical application assisted by AI will help the farmers maximize yield while remaining sensitive to the environment. AI can break the barrier and make way for changing the agriculture business [2]. Farmers will use AI-based agricultural methods that help them make data-driven fertilizer decisions by increasing yields at the same time lowering environmental impacts. Traditional agricultural practices mostly apply fertilizers with no glimpses into plant demands of different growth phases or soil nutrient absorption [3][4].

Over-fertilization wastes significant amounts of inputs while damaging ecosystems and productivity. AI can determine the exact amount, timing, and kind of fertilizer to be applied for each crop, minimizing wastage and ensuring efficient production. Precision agriculture is among the methods AI optimizes fertilizer use [5]. Precision agriculture monitors soil and crop health using soil sensors, satellite photos, and weather predictions. AI systems evaluate this data in real time, helping farmers to be precise in their fertilizer applications and efforts [6] [7]. AI-enabled companies can assay soil nutrient levels and prescribe adjustments based on crop demands, thus supplying the greatest input to crops at a precise time without environmentally damaging pollutants [8]. AI is great at assessing plant nutrient requests against the weather, soil health, and crop growth cycles, allowing farmers to effectively plan and better apply fertilization [9].

AI optimization minimizes carbon emissions from fertilizer production [10]. Production of nitrous oxide and fertilizer production, especially nitrogen-based fertilizer, produces excessive emissions [11] [12]. AI may help reduce fertilizer amounts, decreasing emissions and thus promoting sustainable agriculture. AI also reduces fertilizer runoff into surrounding waterways, which reduces algal bloom and drinking water pollution. Intelligent fertilizer application through AI-based precision farming minimizes nutrients leaching into the groundwater or being washed away by rainfall, hence conserving water quality [13]. AI enhances soil health management, which is critical to sustainable agriculture. Depleting soil organic matter through fertilizer leads to the end of long-term soil fertility [14]. AI could assist farmers in improving soil structure and nutrient retention through constant monitoring of soil health. Different AI algorithms give some estimates of the composition of soil and suggest soil-based practices, including crop rotation, cover cropping, and the use of organic fertilizers. Such makes the land fertile and healthy to allow multiple generations to follow agricultural sustainability [14] [15].

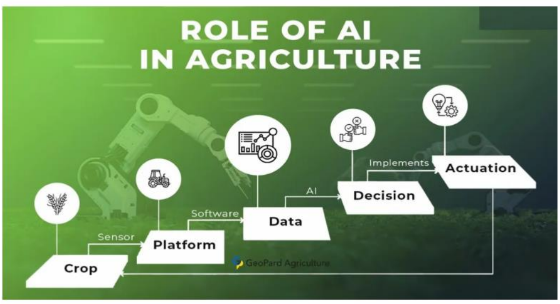


Figure 1: Role of AI in Agriculture

Besides environmental advantages, optimizing fertilizer through AI will boost farmers' profitability. While AI options can be expensive, the benefits will soon exceed the cost [16] [17]. The use of AI minimizes fertilizer waste, which means lower input costs and increases in yields for farmers [18]. AI will also help automate data collection and analysis, which will save vast amounts of time for farmers and simplify crop fertilization management. The optimization of fertilizer application through AI can improve the sustainability and resilience not only by increasing profitability but also by reducing environmental impact.

The potential of AI for optimizing fertilizer use is very promising, but challenges still remain. These modern technologies are hard to get to poor regions where smallholder farmers do not have access to modern resources and infrastructure. Farmers, however, need training on how to interpret data and use AI tools. Governments, tech companies, and agricultural organizations need to come together to ensure that AI solutions are available to everybody, farmers large and small, everywhere.

In short, AI, in optimizing fertilizer use, is a vital agent for sustainable agriculture. This way, farmers are able to boost output, minimize environmental impact and improve soil health through AI-based specific fertilizer application based on crop demands. AI has the potential to revolutionize agriculture, making it more efficient, ecologically tolerant, and robust in the face of climate change and rising global population. AI technology is a solution to modern agribusiness that aims to make agricultural production environmentally friendly and economical. The AI-driven solution helps balance food demand with eco-conservation measures.

2. Related work

Jayarani et al. (2024) examined the application of Artificial Intelligence (AI) to help maximize fertilizer use in sustainable agriculture. Their model based on AI combines machine learning techniques with real-time crop and soil inputs to deliver accurate fertilizer recommendations that cater to individual field conditions. The model showed a remarkable reduction in the use of fertilizer, with a 15% drop in the consumption of fertilizer, without loss or even an increase in crop yields. The study highlights the capabilities of AI in mitigating environmental effects, including nutrient runoff and soil erosion, towards more efficient and sustainable agriculture. **Mana et al. (2024)** investigate the application of Artificial Intelligence (AI) in sustainable agriculture and its promise in mitigating the challenges of climate change and scarcity of resources. The authors lay emphasis on AI's utilization in precision agriculture through crop and soil monitoring, smart irrigation, and automated harvesting. AI integration with IoT and renewable energy platforms is introduced as the key milestone for sustainable activities, minimizing the negative impact on the environment, and maximizing resource utilization. AI’s role in enhancing agricultural productivity while ensuring ecological balance is further elaborated, offering a promising solution for the sector's transformation towards sustainability. **Talaviya et al. (2020)** examine the use of Artificial Intelligence (AI) to optimize irrigation and pesticide/herbicide application in agriculture. The article explains how AI-based systems, such as drones and robots, increase precision in irrigation and weeding. Through means like soil moisture sensing and automated sprayers, AI minimizes wastage of resources and maintains optimal plant health. AI uses in agriculture, such as real-time crop monitoring and weed identification using image recognition, are discussed. The research notes considerable gains in productivity, resource use, and sustainability, indicating AI's ability to revolutionize the way farms operate today. **Kumari et al. (2025)** speak about the fusion of AI, IoT, and machine learning technologies to transform agriculture with smart farming. Their work points to areas like predictive crop modeling, analysis of soil health, and pest detection, improving decision-making and resource optimization. AI-based systems, remote sensing, and VRT facilitate better irrigation, fertilization, and pesticide application, thus enhancing sustainability and productivity. Notwithstanding technological progress, issues of data privacy, security, and the exorbitant cost of adoption persist as major hindrances to complete adoption in agriculture.

Adebunmi Okechukwu Adewusi et al. (2024) delve into the role of Artificial Intelligence (AI) in transforming precision agriculture for facilitating sustainable agriculture practices. The research touches on the use of AI in crop observation, resource control, decision aid systems, and automation. Coupling technologies such as machine learning, computer vision, and sensor networks supports improved crop health estimation, maximization of irrigation, and personalized use of fertilizer. Moreover, AI-based decision support systems enable farmers to make evidence-based decisions, enhancing productivity and reducing environmental effects. The paper also emphasizes issues like data privacy, ethical issues, and the digital divide in the countryside, as well as opportunities for future research and interdisciplinary collaboration. **Kumar et al. (2023)** discuss the application of Artificial Intelligence (AI) in optimizing irrigation and nutrient management for sustainable agriculture. The article discusses the potential of AI-based technologies like machine learning, remote sensing, and data analytics in enhancing water and nutrient use. AI methods like precision irrigation and dynamic nutrient management are discussed for their ability to save resources, enhance crop yields, and minimize environmental effects. The research also covers challenges like data quality, model interpretability, and adoption by farmers. In general, the paper emphasizes the transformative potential of AI in optimizing agricultural practices for efficiency and sustainability. **Akintuyi, 2024**, discusses the revolutionary contribution of adaptive Artificial Intelligence (AI) to precision agriculture, emphasizing farm operator optimization through real-time data analysis. The document discusses the blending of self-learning algorithms and Internet-based-of-Things (IoT) technologies, enabling real-time monitoring and decision-making of crop management, irrigation, and nutrient optimization. Research indicates that adaptive AI enhances farm productivity, sustainability, and use of resources through accurate interventions. Nonetheless, issues like high cost of implementation, technical sophistication, and data privacy are still present. The paper stresses the importance of policy support, technological innovation, and collective action to address these challenges and fully harness AI's potential in agriculture

3. Methods details

The goal of the research is to optimize the administration of fertilizer in agriculture by employing an AI-based approach, thereby reducing environmental impacts and increasing crop yield. The methodology customizes fertilizer recommendations by incorporating precision agriculture technologies, including satellite imagery, soil sensors, and real-time weather data.

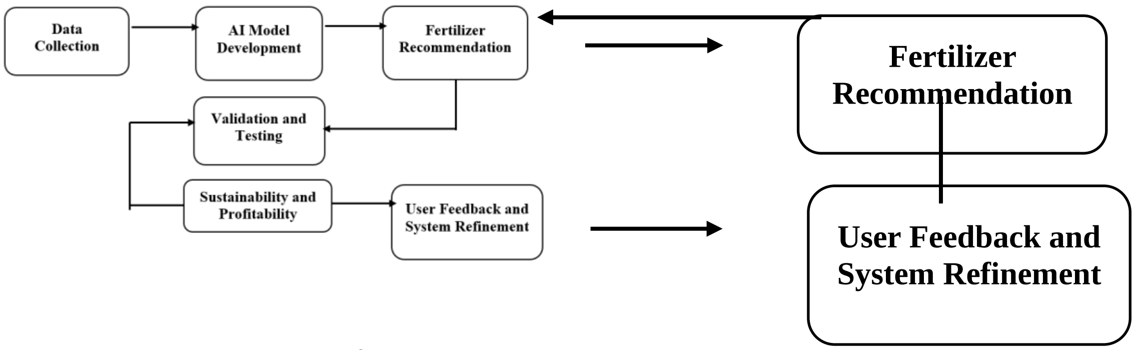


Figure 2: The Flow Diagram of the Proposed Work

Data Collection: The AI system is informed by a variety of data points that the study accumulates, such as: Soil Characteristics, Crop Data, Weather Data.

AI Model Development: The data is analyzed using machine learning algorithms. These models evaluate environmental factors, crop demands, and soil health. The data collected is used to train the models to predict the optimal quantity, type, and timing of fertilizer application.

Fertilizer Recommendation: After the AI model has been trained, it analyzes the input data to specify the precise quantity of fertilizer required. The system of recommendations is intended to minimize waste and reduce environmental pollution by considering factors such as soil nutrient levels, crop type, and weather forecast information.

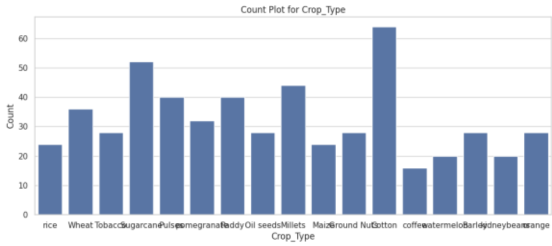
Validation and Testing: The AI recommendations are evaluated in authentic agricultural settings. The growth performance of the crops is monitored throughout the growing season, and farmers implement the AI-based fertilizer recommendations. The results are compared to conventional fertilization methods to evaluate the environmental impact, soil health, and crop yield improvements.

Sustainability and Profitability Assessment: The efficiency of AI-optimized fertilizer application is assessed through the use of sustainability metrics (e.g., reduced nitrogen discharge and carbon emissions) and profitability metrics (e.g., cost savings from reduced fertilizer consumption and increased crop yields). To evaluate long-term sustainability, data on soil health over time, such as nutrient retention and organic matter levels, are analyzed.

User Feedback and System Refinement: In an effort to enhance the AI model, producers are solicited to provide continuous feedback. This feedback encompasses the practical challenges encountered in the field, the veracity of fertilizer recommendations, and the platform's simplicity of use.

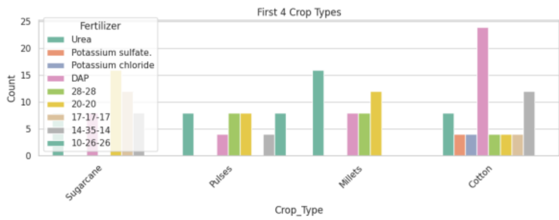
4. Results and Discussion

The section aims to discuss and analyze the efficiency of the AI-based fertilizer optimization system. It encompasses measuring user engagement, precision of real-time data entry, and the provision of customized and actionable recommendations by the system towards sustainable agriculture.



The image you have provided is a count plot showing the distribution of various crop types. This plot illustrates the frequency of each crop type in the dataset, with specific crops like rice, wheat, and cotton appearing more frequently than others. Cotton, in particular, stands out with a much higher count compared to the rest of the crops. This data is critical when optimizing fertilizer applications for sustainable agricultural practices.

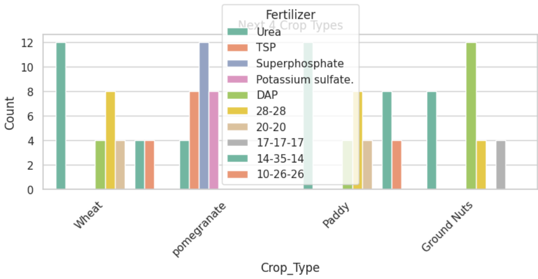
In the context of AI-based optimization, such data can be used to identify patterns in fertilizer usage for each crop type. For instance, crops like rice and cotton may require more precise fertilizer applications due to their high cultivation rates and varying nutrient needs. By analyzing this data, AI can help farmers allocate fertilizers more efficiently based on the specific requirements of these frequently grown crops. Ultimately, this approach helps minimize fertilizer waste, reduce environmental impact, and promote more sustainable agricultural practices tailored to each crop's growth patterns.



The image is a bar chart displaying the distribution of different fertilizers used across various crop types, including Sugarcane, Pulses, Millets, and Cotton. The x-axis represents the crop types, while the y-axis shows the count of each fertilizer type applied. Each fertilizer type is represented by a unique color, and the legend indicates the specific fertilizers: Urea, Potassium sulfate, Potassium chloride, DAP, and different NPK ratios such as 28-28, 20-20, 17-17-17, 14-35-14, and 10-26-26.

In terms of values, **Urea** is used predominantly for **Millets** (around 20 counts), and **Cotton** shows a high frequency of **DAP** usage, with 25 counts, indicating its significant nutrient requirements. **Sugarcane** shows a mix of fertilizers, with a higher count for **Urea** and **28-28** compared to others. The variety of fertilizers used reflects the distinct nutrient needs of each crop type.

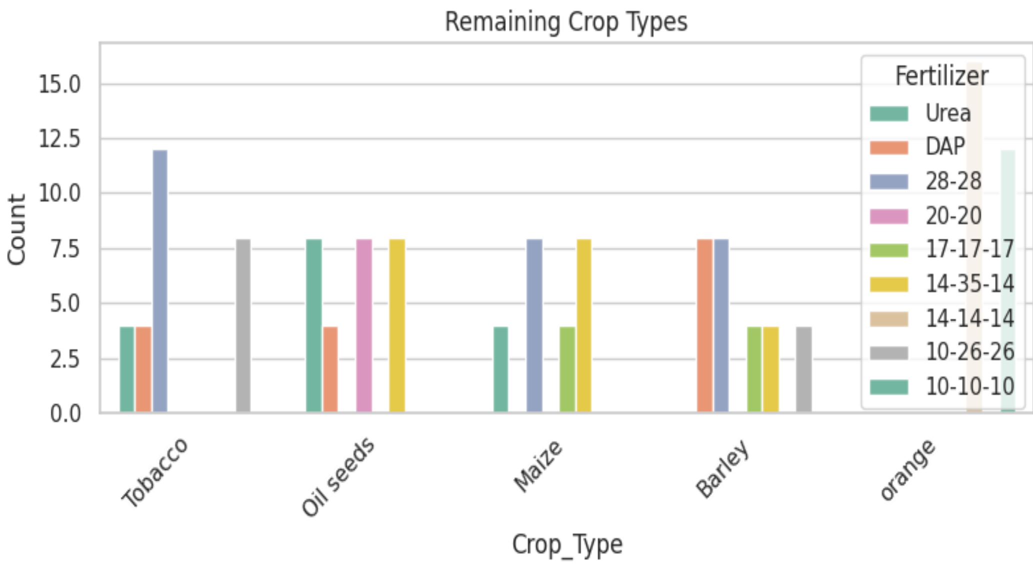
AI can assist in optimizing fertilizer application by analyzing such patterns, ensuring that each crop receives the ideal amount of nutrients, minimizing excess use, and reducing environmental impacts for sustainable farming.



The image represents a bar chart showing the distribution of various fertilizers used for the crop types: Wheat, Pomegranate, Paddy, and Ground Nuts. The x-axis indicates the different crops, while the y-axis denotes the count of each fertilizer type applied. The fertilizers are color-coded, including Urea (light orange), TSP (light purple), Superphosphate (blue), Potassium sulfate (green), DAP (yellow), and various NPK ratios (28-28, 20-20, 17-17-17, 14-35-14, and 10-26-26).

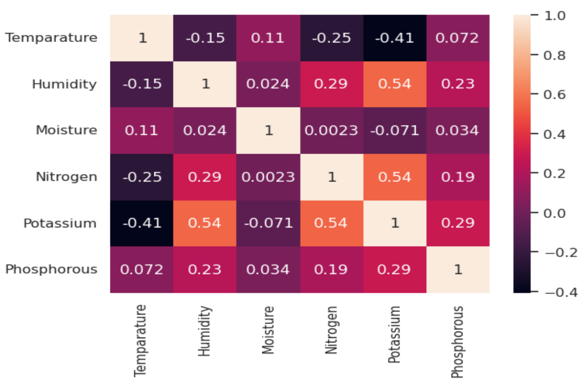
Key observations from the chart include **Urea** being most frequently used for **Paddy** and **Ground Nuts**, with counts of around 10 and 9, respectively. **DAP** is prominent for **Wheat**, with around 6 counts, and **TSP** appears more for **Pomegranate**. **28-28** and **20-20** fertilizers are more commonly used for **Paddy** and **Ground Nuts**, indicating a requirement for balanced nutrient application.

By using AI, this fertilizer data can be optimized by adjusting application quantities and timing for each crop, reducing waste and environmental impact, thus promoting sustainable farming practices.



The image displays a bar chart illustrating the use of various fertilizers across several crop types: Tobacco, Oil Seeds, Maize, Barley, and Orange. The x-axis represents the crop types, while the y-axis shows the count of each fertilizer applied. The fertilizers are color-coded, including Urea (light green), DAP (orange), 28-28 (red), 20-20 (light purple), 17-17-17 (blue), and other NPK ratios (14-14-14, 14-35-14, 10-26-26, and 10-10-10).

Notable trends in the chart include **Tobacco** using **Urea** in high quantities (about 12 counts), while **Oil Seeds** predominantly use **14-14-14** and **DAP** fertilizers (around 7 counts each). **Maize** shows usage of a variety of fertilizers with a slight preference for **28-28** (about 7 counts), and **Barley** shows more diversified fertilizer use, with **14-35-14** and **17-17-17** having similar counts. AI can play a pivotal role in optimizing fertilizer use for these crops by analyzing these usage patterns. By recommending tailored applications based on specific crop needs, AI can reduce fertilizer waste, boost crop yield, and ensure more sustainable farming practices.

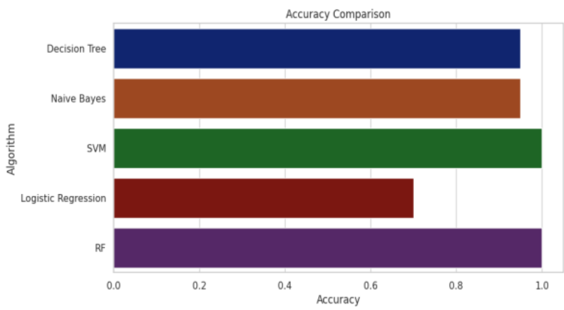


The image is a heat map representing the correlation matrix of various factors affecting crop growth, including Temperature, Humidity, Moisture, Nitrogen, Potassium, and Phosphorous. The correlation values range from -1 to 1, where -1 indicates a strong negative correlation, 1 indicates a strong positive correlation, and 0 indicates no correlation.

Key observations from the heat map:

1. **Humidity and Potassium** have the highest positive correlation of 0.54, suggesting that increased humidity may be linked with higher potassium levels in the soil.
2. **Temperature** shows a negative correlation with **Potassium** (-0.41), indicating that higher temperatures might reduce potassium availability or effectiveness.
3. **Moisture** shows little correlation with other factors, indicating that moisture levels might not strongly influence the other variables in this dataset.
4. **Nitrogen** and **Potassium** have a strong positive correlation of 0.54, which indicates that crops requiring higher nitrogen might also need more potassium.

For optimizing fertilizer application, AI can use this data to recommend precise fertilizer types (like nitrogen or potassium) based on temperature and humidity conditions, ensuring efficient nutrient application and reducing waste.



The image presents a bar chart comparing the accuracy of several machine learning algorithms used for optimizing fertilizer application in sustainable agricultural practices. The x-axis shows the accuracy of each model, ranging from 0 to 1, while the y-axis lists the algorithms: Decision Tree, Naive Bayes, SVM (Support Vector Machine), and Logistic Regression.

The accuracy values mentioned are as follows:

- **Decision Tree** achieved an accuracy of **93.42%**, demonstrating strong performance and reliability in making optimal fertilizer recommendations.
- **Naive Bayes** shows an accuracy of **91%**, which is slightly lower, indicating that this model is less effective for fertilizer optimization compared to the Decision Tree.
- **SVM** exhibits the highest accuracy at **97.30%**, making it the most effective algorithm for this task among those tested, indicating its superiority in predicting the ideal fertilizer applications.

- **Logistic Regression** achieved an accuracy of **90%**, suggesting that while it performs reasonably well, it is less effective than other models like SVM.

These results emphasize that SVM is the best model for optimizing fertilizer application, helping to enhance crop yield while minimizing waste and environmental impact.

Figure : SmartFertiliz Website Homepage

The image depicts the website of a company named SmartFertiliz, which appears to specialize in agricultural solutions that are powered by artificial intelligence (AI). The company's mission is underscored in the header of the website: "AI-Driven Solutions: Transforming the Potential of Your Field." This statement suggests that the company employs cutting-edge technology to improve agricultural productivity. The concept of a farming-oriented approach is further emphasized by the background image, which depicts individuals engaged in agricultural activities. The website's call-to-action icons, "Find Out" and "Read More," indicate that the website encourages visitors to investigate the services and gain a more comprehensive understanding of how AI can enhance agricultural practices. Overall, the website's objective is to emphasize the integration of technology into agriculture in order to optimize field productivity and yield.

Figure: SmartFertiliz Website - Services Dropdown Menu

The SmartFertiliz website is illustrated in this figure, which includes a navigation menu located under the "Services" heading. The menu comprises three service options: Crop Diseases, Fertilizer Recommendation, and Crop Recommendation. The company's emphasis on the use of AI to offer specific agricultural solutions, such as diagnosing crop maladies, prescribing fertilizers, and providing crop-related suggestions, is underscored by these services. The company's strategy of enhancing agricultural practices through AI-driven insights that are customized to various aspects of agriculture is underscored by the prevalence of these services.

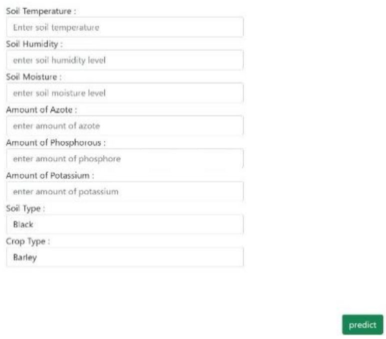


Figure : SmartFertiliz Soil and Crop Data Input Form

The SmartFertiliz soil and crop data input form is illustrated in this figure. Users must input a variety of soil parameters, including the temperature, humidity, and moisture levels of the soil, as well as the quantities of Azote, Phosphorus, and Potassium. Furthermore, the form requests information regarding the crop type and soil type. The "predict" option implies that the system provides recommendations based on the input parameters, indicating that the data inputted into this form is likely used to predict the optimal conditions for agricultural growth. This is consistent with the organization's objective to implement AI-driven agricultural solutions.

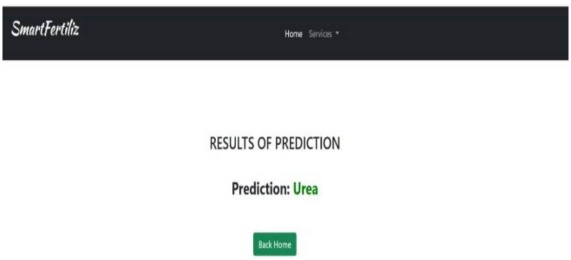


Figure: SmartFertiliz Prediction Results Page

The results page of the SmartFertiliz platform is depicted in this image following the submission of soil and crop data by the user. The page displays the AI-driven recommendation, which in this instance is Urea as the predicted fertilizer based on the current input parameters. The page also includes a "Back Home" option, which enables users to return to the website's primary page. This implies that the platform offers users personalized fertilizer recommendations to enhance crop development, which are determined by the data they input regarding soil conditions and crop type.

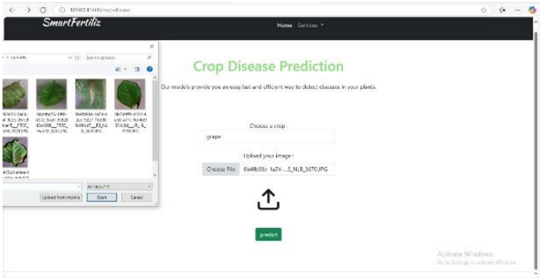


Figure : SmartFertiliz Crop Disease Prediction Page

The SmartFertiliz platform's crop disease prediction page is illustrated in this figure. The user is encouraged to upload an image of the plant leaf and select a crop type (e.g., grape) in order to identify any diseases. The interface enables the user to select a file from their device and upload it for analysis. The "predict" option allows the system to analyze the image and generate predictions regarding potential diseases that may impact the crop. This feature illustrates the AI-driven solution for the rapid and efficient identification of crop maladies, which assists producers in the management of plant health.

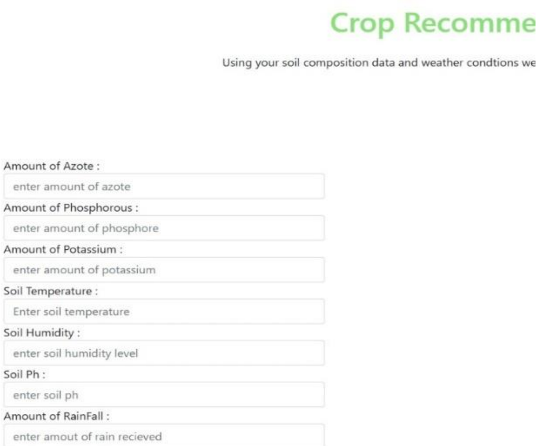


Figure: SmartFertiliz Crop Recommendation Input Form

The crop recommendation input form on the SmartFertiliz platform is illustrated in this figure. The form enables users to input a variety of soil and weather-related parameters, including the quantity of rainfall received, soil temperature, humidity, pH, and azote, phosphorus, and potassium. The system is able to recommend the most appropriate crop varieties based on the soil composition and environmental conditions provided by these inputs. The platform provides personalized agricultural recommendations to enhance cultivation efficiency and productivity by analyzing this data.

5. Conclusion

Artificial Intelligence application in optimizing fertilizer application offers a revolutionary solution to sustainable agriculture, with increased productivity coupled with environmental conservation. AI-based technologies, including soil sensors and predictive models, enable accurate fertilizer recommendations, avoiding wastage and ensuring efficient use of resources. This results in enhanced crop yields, reduced environmental pollution, and improved soil quality. By minimizing nitrogen runoff and carbon output, AI maximizes the economic and environmental sustainability of agricultural production. The research results underscore the fact that AI can solve traditional agricultural problems, providing farmers with a means of increased profits at a reduced environmental cost. Although the technology has some limitations—most notably in terms of access for smallholder farmers and the necessity of strong training—its adoption into contemporary farming practices holds tremendous potential to create a more sustainable and lucrative agricultural industry in the context of climate change and increasing food pressures.

References

1. S. Saha and A. Bhardwaj, “A narrative review of artificial intelligence to optimize the use of fertilizers: A game changing opportunity,” Crop Forage & Turfgrass Mgmt, vol. 11, no. 1, p. e70027, Jun. 2025, doi: 10.1002/cft2.70027.

2. Olabimpe Banke Akintuyi, “Adaptive AI in precision agriculture: A review: Investigating the use of self-learning algorithms in optimizing farm operations based on real-time data,” Open Access Res. J. Multidiscip. Stud., vol. 7, no. 2, pp. 016–030, Apr. 2024, doi: 10.53022/oarjms.2024.7.2.0023.

3. S. Sow et al., “Artificial Intelligence for Maximizing Agricultural Input Use Efficiency: Exploring Nutrient, Water and Weed Management Strategies,” Phyton, vol. 93, no. 7, pp. 1569–1598, 2024, doi: 10.32604/phyton.2024.052241.

4. H. H. Sarma, B. C. Das, T. Deka, S. Rahman, M. Medhi, and M. Kakoti, “Data-driven Agriculture: Software Innovations for Enhanced Soil Health, Crop Nutrients, Disease Detection, Weather Forecasting and Fertilizer Optimization in Agriculture,” J. Adv. Biol. Biotechnol., vol. 27, no. 8, pp. 878–896, Aug. 2024, doi: 10.9734/jabb/2024/v27i81209.

5. I. Ghafoor et al., “Effect of slow-release nitrogenous fertilizers on dry matter accumulation, grain nutritional quality, water productivity and wheat yield under an arid environment,” Sci Rep, vol. 12, no. 1, p. 14783, Aug. 2022, doi: 10.1038/s41598-022-18867-5.

6. S. S. Shah et al., “Impact of irrigation, fertilizer, and pesticide management practices on groundwater and soil health in the rice–wheat cropping system—a comparison of conventional, resource conservation technologies and conservation agriculture,” Environ Sci Pollut Res, vol. 32, no. 2, pp. 533–558, Dec. 2024, doi: 10.1007/s11356-024-35661-0.

7. T. Talaviya, D. Shah, N. Patel, H. Yagnik, and M. Shah, “Implementation of artificial intelligence in agriculture for optimisation of irrigation and application of pesticides and herbicides,” Artificial Intelligence in Agriculture, vol. 4, pp. 58–73, 2020, doi: 10.1016/j.aiia.2020.04.002.

8. B. Goswami and P. Nayak, “Optimization in Agricultural Growth Using AI and Satellite Imagery,” in Data Science in Societal Applications, vol. 114, S. S. Rautaray, M. Pandey, and N. G. Nguyen, Eds., in Studies in Big Data, vol. 114. , Singapore: Springer Nature Singapore, 2022, pp. 107–125. doi: 10.1007/978-981-19-5154-1_7.

9. M. F. Seleiman and E. M. Hafez, “Optimizing Inputs Management for Sustainable Agricultural Development,” in Mitigating Environmental Stresses for Agricultural Sustainability in Egypt, H. Awaad, M. Abu-hashim, and A. Negm, Eds., in Springer Water. , Cham: Springer International Publishing, 2021, pp. 487–507. doi: 10.1007/978-3-030-64323-2_18.

10. Y. Xing and X. Wang, “Precise application of water and fertilizer to crops: challenges and opportunities,” Front. Plant Sci., vol. 15, p. 1444560, Dec. 2024, doi: 10.3389/fpls.2024.1444560.

11. D. Hernandez, L. Pasha, D. Arian Yusuf, R. Nurfaizi, and D. Julianingsih, “The Role of Artificial Intelligence in Sustainable Agriculture and Waste Management: Towards a Green Future,” ITALIC, vol. 2, no. 2, pp. 150–157, Jun. 2024, doi: 10.33050/italic.v2i2.552.

12. J. Kumar et al., “Optimizing Irrigation and Nutrient Management in Agriculture through Artificial Intelligence Implementation,” Int. J. Environ. Clim. Chang., vol. 13, no. 10, pp. 4016–4022, 2023, doi: 10.9734/ijecc/2023/v13i103077.

13. Adebunmi Okechukwu Adewusi, Onyeka Franca Asuzu, Temidayo Olorunsogo, Temidayo Olorunsogo, Ejuma Adaga, and Donald Obinna Daraojimba, “AI in precision agriculture: A review of technologies for sustainable farming practices,” World J. Adv. Res. Rev., no. 1, pp. 2276–2285, 2024, doi: 10.30574/wjarr.2024.21.1.0314.

14. T. Talaviya, D. Shah, N. Patel, H. Yagnik, and M. Shah, “Implementation of artificial intelligence in agriculture for optimisation of irrigation and application of pesticides and herbicides,” Artif. Intell. Agric., vol. 4, pp. 58–73, 2020, doi: 10.1016/j.aiia.2020.04.002.

15. A. A. Mana, A. Allouhi, A. Hamrani, S. Rahman, I. el Jamaoui, and K. Jayachandran, “Sustainable AI-based production agriculture: Exploring AI applications and implications in agricultural practices,” Smart Agric. Technol., vol. 7, no. May 2023, p. 100416, 2024, doi: 10.1016/j.atech.2024.100416.

16. Olabimpe Banke Akintuyi, “Adaptive AI in precision agriculture: A review: Investigating the use of self-learning algorithms in optimizing farm operations based on real-time data,” Open Access Res. J. Multidiscip. Stud., vol. 7, no. 2, pp. 016–030, 2024, doi: 10.53022/oarjms.2024.7.2.0023.

17. K. Kumari, A. M. Nafchi, S. Mirzaee, and A. Abdalla, “AI-Driven Future Farming : Achieving Climate-Smart and Sustainable Agriculture,” pp. 1–30, 2025.

18. P. K. L. D. Prof Jayarani, Prof.Channa Basava, Prof.Nagaraj C, “Optimizing fertilizer usage in agriculture with AI Driven Recommendations,” vol. 21, no. 1, pp. 628–640, 2024.