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Machine Learning Approaches for Climate-Driven Disease Prediction

B. M. Chaudhari and *P. G. Gameti

B. A. College of Agriculture, Anand Agricultural University, Anand, Gujarat, India

*Corresponding Author's email: gametiprincy28@gmail.com

Climate change is increasingly influencing the emergence, spread, and severity of plant diseases, posing significant risks to global food security. Variations in temperature, humidity, and precipitation patterns create favorable conditions for pathogen development and disease outbreaks. Traditional disease forecasting approaches often fail to capture the complexity of climate–disease interactions. In this context, machine learning (ML) has emerged as a powerful tool for climate-driven disease prediction by analyzing large and complex datasets. This review synthesizes recent advancements in ML and deep learning techniques for predicting plant diseases under changing climatic conditions. It highlights the integration of meteorological data, remote sensing inputs, and historical disease records to improve predictive accuracy. The study also discusses applications in crop disease forecasting, challenges related to data quality and model generalization, and future directions for developing robust climate-resilient prediction systems. The findings emphasize the critical role of ML in enabling proactive disease management and sustainable agricultural practices.

Keywords: Machine Learning; Climate Change; Plant Disease Prediction; Deep Learning; Climate-Smart Agriculture; Predictive Modeling; Big Data; Crop Protection

Introduction

Climate change refers to long-term alterations in temperature regimes and weather patterns at global or regional scales. While such changes can arise from natural processes, recent trends are predominantly driven by anthropogenic activities. Notably, the decade spanning 2016–2025 has been the warmest on record, and each of the past four decades has exhibited higher average temperatures than any preceding decade since 1850. It has emerged as a major driver of plant disease dynamics, influencing pathogen distribution, host susceptibility, and disease severity. Changes in temperature, rainfall patterns, and humidity create favorable conditions for the emergence and spread of plant pathogens. These climate-induced variations often result in unpredictable disease outbreaks, posing significant challenges to agricultural sustainability and food security (Garrett *et al.*, 2022; Iqbal & Naqvi, 2025).

Traditional disease prediction models are largely based on empirical relationships wherein predefined functional forms are used to relate (they assume linear or simplified non-linear relationships) disease incidence or severity to a limited set of climatic variables, they often fail to capture the complex interactions between climatic variables and disease development. In recent years, machine learning (ML) approaches have gained prominence due to their ability to process large datasets and identify nonlinear patterns. ML models can integrate diverse data sources, including meteorological data, crop characteristics, and historical disease records, to provide accurate and timely predictions (Kaur *et al.*, 2026; Recalde *et al.*, 2025).

The integration of ML with climate data has opened new opportunities for developing climate-resilient disease prediction systems. These systems enable early warning, support decision-making, and facilitate sustainable crop management practices.

Climate Change and Disease Dynamics

Climate change significantly alters the epidemiology of plant diseases by influencing pathogen life cycles and host–pathogen interactions. Increased temperatures can accelerate pathogen development, while changes in precipitation patterns can affect spore dispersal and infection rates. Similarly, humidity plays a crucial role in disease establishment and progression.

Recent studies have highlighted that climate variability not only increases the frequency of disease outbreaks but also expands the geographical range of pathogens. This creates new challenges for disease management and necessitates the development of predictive models that can account for climate variability (Ngaiza *et al.*, 2026). The complex interplay between climatic factors and disease dynamics requires advanced analytical tools capable of handling large datasets and capturing nonlinear relationships. Machine learning provides a suitable framework for addressing these challenges.

Machine Learning Techniques for Disease Prediction

Machine learning encompasses a wide range of algorithms that can be applied to disease prediction. These include supervised learning methods such as decision trees, support vector machines, and random forests, as well as deep learning approaches such as neural networks and convolutional neural networks. Deep learning models, in particular, have shown significant potential in capturing complex relationships between climatic variables and disease occurrence. These models can analyze large datasets and automatically extract relevant features, improving prediction accuracy (Das *et al.*, 2026).

Recent advancements in ensemble learning and hybrid models have further enhanced prediction performance. For example, frameworks combining multiple algorithms with hyperparameter tuning have been developed for predicting diseases in crops such as tomato under varying climatic conditions (Sharma, 2025). Similarly, advanced architectures such as long short-term memory (LSTM) networks and transformer-based models have been used for time-series forecasting of disease outbreaks (Attri *et al.*, 2026).

Integration of Climate Data and Machine Learning

The effectiveness of machine learning models in disease prediction depends largely on the quality and diversity of input data. Climate-driven disease prediction models typically integrate meteorological variables such as temperature, humidity, rainfall, and wind patterns with crop and disease data. Big data platforms and AI-driven systems have been developed to facilitate the integration and analysis of large datasets. For instance, systems like AgriClimateAI utilize big data and machine learning to monitor the impact of climate on agriculture and predict disease outbreaks (Shankar & Madhusudhan). Remote sensing and satellite data further enhance prediction capabilities by providing real-time information on crop health and environmental conditions. AI-powered systems that combine satellite imagery with meteorological data have demonstrated high accuracy in predicting climate-driven crop failures and disease outbreaks (Banaganapalli & Janga, 2025).

Applications in Climate-Smart Agriculture

Machine learning-based disease prediction models are increasingly being used in climate-smart agriculture to improve crop resilience and productivity. These models enable early detection of disease risks, allowing farmers to implement timely management strategies. In maize cultivation, machine learning algorithms have been used to forecast pest populations such as fall armyworm based on climatic conditions, enabling proactive pest management (Kalisetti *et al.*, 2025). Similarly, ML models have been applied to predict disease outbreaks in fruit crops by analyzing climate-induced stress factors (Iqbal & Naqvi, 2025). These applications demonstrate the potential of ML in supporting sustainable agriculture by optimizing resource use and reducing crop losses.

Challenges and Limitations

Despite the significant potential of machine learning in climate-driven disease prediction, several challenges remain. One of the major limitations is the availability of high-quality, labeled datasets. In many regions, reliable data on disease occurrence and climatic conditions are scarce, limiting model accuracy. Another challenge is the generalization of models across different geographic regions. Models trained in one location may not perform well in other regions due to variations in climate, crop varieties, and pathogen strains (Recalde *et al.*, 2025). High computational requirements and the need for technical expertise also pose barriers to the adoption of ML technologies. Additionally, issues related to data privacy and integration of heterogeneous data sources need to be addressed.

Future Perspectives

Future research should focus on developing robust and scalable machine learning models that can adapt to diverse climatic conditions. The integration of explainable AI techniques can improve model transparency and facilitate decision-making. Advances in cloud computing and edge computing can enhance the efficiency of data processing and enable real-time predictions. Collaborative efforts among researchers, policymakers, and stakeholders are essential for developing standardized datasets and promoting the adoption of ML technologies in agriculture. Furthermore, integrating ML models with climate-resilient disease management strategies can significantly enhance agricultural sustainability and food security.

Conclusion

Machine learning approaches are playing a crucial role in predicting climate-driven plant diseases by enabling accurate analysis of complex interactions between climatic variables and disease dynamics. The integration of ML with climate data and remote sensing technologies provides powerful tools for early warning and proactive disease management. While challenges related to data availability, model generalization, and technical complexity remain, ongoing advancements in AI and data science are expected to overcome these limitations. The adoption of ML-based prediction systems will be essential for developing climate-resilient agriculture and ensuring global food security.

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