Role of Artificial Intelligence and Remote Sensing in Early Detection of Plant Diseases

[1]P. G. Gameti and [2]B. M. Chaudhari

[1]Ph.D. Scholar (Plant Pathology), Department of Plant Pathology,

[2]Ph.D. Scholar (Agricultural Meteorology), Department of Agricultural Meteorology

B. A. College of Agriculture, Anand Agricultural University, Anand - 388 110

Corresponding Email: gametiprincy28@gmail.com

Abstract

Plant diseases are a major constraint to global agricultural productivity, leading to significant yield losses and threatening food security. Early detection is essential for effective disease management; however, conventional diagnostic methods are often limited by delayed symptom expression and subjective assessment. Recent advancements in artificial intelligence (AI) and remote sensing technologies have revolutionized plant disease detection by enabling rapid, non-invasive, and large-scale monitoring. This review synthesizes recent developments in hyperspectral imaging, unmanned aerial vehicle (UAV)-based sensing, and AI-driven analytical models for early disease diagnosis. The integration of AI with remote sensing enhances detection accuracy and supports predictive disease modeling. Despite substantial progress, challenges such as limited datasets, high implementation costs, and issues related to model generalization persist. Future research should focus on developing scalable, cost-effective, and robust systems to ensure sustainable crop protection and global food security.

Keywords

Artificial Intelligence; Remote Sensing; Plant Disease Detection; Deep Learning; Hyperspectral Imaging; UAV; Precision Agriculture; Early Diagnosis

1. Introduction

Plant diseases continue to pose a serious threat to global agriculture, causing substantial yield losses and affecting crop quality. Timely detection is critical for minimizing damage and implementing effective management strategies. Traditional disease detection methods, primarily based on visual inspection and laboratory analysis, are often labor-intensive, time-consuming, and ineffective in identifying infections at early stages (Rani *et al.*, 2023; Jafar *et al.*, 2024).

The emergence of artificial intelligence (AI) and remote sensing technologies has significantly transformed plant disease diagnostics. These technologies enable continuous monitoring of crop health, detection of subtle physiological changes, and prediction of disease outbreaks. The integration of AI with remote sensing provides a powerful framework for precision agriculture, allowing farmers to make informed decisions and optimize resource use (Mahlein *et al.*, 2024; Aziz *et al.*, 2025).

2. Remote Sensing for Early Disease Detection

Remote sensing is a non-destructive technique that enables the monitoring of plant health by capturing spectral information from crops using sensors mounted on satellites, drones, or ground-based platforms. Diseased plants exhibit distinct spectral signatures due to changes in physiological and biochemical properties, including chlorophyll degradation, water stress, and cellular damage (Gogoi *et al.*, 2018).

Hyperspectral imaging has emerged as a powerful tool for early disease detection due to its ability to capture detailed spectral information across a wide range of wavelengths. This allows for the identification of subtle plant stress signals before visible symptoms appear. Hyperspectral data have been successfully used to distinguish between healthy and infected plants at early stages of disease development (Terentev *et al.*, 2022). Multispectral imaging, although less detailed, offers a more cost-effective alternative and is widely used in practical agricultural applications. Vegetation indices derived from multispectral data are commonly employed to assess crop health and detect disease stress.

The use of unmanned aerial vehicles (UAVs) has further enhanced remote sensing capabilities by providing high-resolution imagery and flexible data acquisition. UAV-based systems enable real-time monitoring and spatial mapping of disease outbreaks. For example, UAV-based remote sensing combined with AI has been successfully applied for early detection of bacterial spot disease in tomato seedlings (da Cunha *et al.*, 2023). Similarly, deep learning techniques applied to UAV imagery have demonstrated high accuracy in detecting crop diseases and pests (Zhu *et al.*, 2024).

3. Artificial Intelligence in Plant Disease Detection

Artificial intelligence has revolutionized plant disease detection by enabling automated analysis of large and complex datasets. Machine learning and deep learning techniques, particularly convolutional neural networks, have shown remarkable performance in image-based disease classification (Ahmed *et al.*, 2025).

AI-based systems can analyze images captured through smartphones, drones, or satellites to detect disease symptoms with high accuracy. These systems facilitate rapid diagnosis and reduce reliance on expert knowledge. Additionally, AI models are capable of performing disease segmentation and severity estimation, providing detailed insights for effective management (Paul *et al.*, 2024; Singh *et al.*, 2025).

Predictive modeling is another significant application of AI in plant pathology. By integrating environmental variables such as temperature, humidity, and rainfall with historical disease data, AI models can forecast disease outbreaks. This enables proactive disease management and helps in minimizing crop losses (Minhans *et al.*, 2025; Taha, 2025).

4. Integration of AI and Remote Sensing

The integration of AI and remote sensing technologies enhances the efficiency and accuracy of plant disease detection systems. Remote sensing provides large-scale, high-resolution data, while AI algorithms process and interpret this data to generate actionable insights. In integrated systems, data are acquired using remote sensing platforms such as UAVs or satellites, followed by preprocessing and feature extraction. AI models are then applied for classification and analysis, enabling real-time disease detection and decision-making.

Advanced platforms such as GeoAgriGuard combine AI and remote sensing to provide real-time monitoring and decision support for disease management (Sharada *et al.*, 2025). Furthermore, the integration of robotics and AI enables automated disease detection and targeted interventions, improving efficiency and reducing labor requirements (Mahlein *et al.*, 2024).

5. Applications in Crop Disease Management

AI and remote sensing technologies have been widely applied across various crops. In rice, these technologies have been used for early detection of blast disease through spectral analysis and machine learning models. In wheat, remote sensing facilitates large-scale monitoring of rust diseases. In horticultural crops such as tomato and vegetables, UAV-based imaging combined with deep learning enables early detection of foliar diseases with high accuracy. These applications demonstrate the potential of AI and remote sensing to improve disease diagnosis, reduce yield losses, and enhance agricultural productivity (Aziz *et al.*, 2025; Sahoo *et al.*, 2024).

6. Challenges and Limitations

Despite significant advancements, several challenges hinder the widespread adoption of AI and remote sensing technologies. One of the major limitations is the lack of large, high-quality labeled datasets required for training robust AI models. Variability in environmental conditions and crop characteristics further complicates model generalization (Jafar *et al.*, 2024).

High costs associated with advanced sensors, UAV systems, and computational infrastructure limit accessibility, particularly for smallholder farmers. Additionally, the implementation of these technologies requires technical expertise, which may not be readily available in developing regions. Another important challenge is the limited transferability of AI models across different geographic and climatic conditions. Addressing these issues is essential for ensuring the scalability and effectiveness of these technologies.

7. Future Perspectives

Future research should focus on developing cost-effective and user-friendly technologies to enhance accessibility. Integration of AI with Internet of Things (IoT) devices and cloud computing platforms can enable real-time monitoring and decision support. Advances in edge computing can further improve efficiency by enabling on-site data processing. Enhancing model robustness through diverse datasets and transfer learning approaches will be critical for improving performance across different environments. Collaborative efforts among researchers, policymakers, and industry stakeholders are necessary to promote the adoption of these technologies and bridge the gap between research and practical application.

8. Conclusion

Artificial intelligence and remote sensing technologies are transforming plant disease detection by enabling early, accurate, and large-scale monitoring of crop health. Their integration provides a powerful approach for precision agriculture and sustainable crop protection. Although challenges related to cost, data availability, and technical complexity remain, ongoing advancements are expected to overcome these barriers. The adoption of these technologies will play a crucial role in enhancing agricultural productivity and ensuring global food security.

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