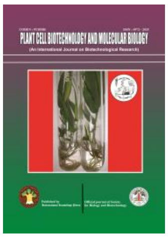

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Advances in Plant Disease Diagnostics and Surveillance- A review

Narsing Laxmi Prasanna [a++], Sushila Choudhary [b#], Sanjay Kumar [c*], Mahima Choudhary [d++], Priyanka Kumari Meena [e], Samreen [f++], Saumya Saloni [g†] and Rajan Ghanghas [h†]

[a] *Department of Plant Pathology, Navsari Agricultural University, Navsari- 396 450, India.*
[b] *Department of Plant Pathology, School of Agriculture, Suresh Gyan Vihar University, Jagatpura, Jaipur- 302017, India.*
[c] *Department of Plant Pathology, Rajmata Vijayaraje Scindia Krishi Vishwavidyalaya, Gwalior- 474002, Madhya Pradesh, India.*
[d] *Department of Plant Pathology, Rajmata Vijayaraje Scindia Krishi Vishwavidyalaya, Gwalior, Madhya Pradesh - 474002, India.*
[e] *Department of Plant Pathology, Sri Karan Narendra Agriculture University, Jobner- Jaipur, Rajasthan - 303329, India.*
[f] *Division of Entomology, ICAR-Indian Agricultural Research Institute, New Delhi-110012, India.*
[g] *Central Agricultural University, Imphal, Manipur-795004, India.*
[h] *Chaudhary Charan Singh Haryana Agricultural University, Hisar – 125001, India.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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[++] *Ph.D. Scholar;*
[#] *Assistant Professor;*
[†] *B.Sc. Student;*
**Corresponding author: E-mail: sparihar734.sp@gmail.com;*

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ABSTRACT

Plant diseases pose a significant threat to global food security, leading to substantial yield losses and economic impacts. Early detection and effective monitoring are crucial for managing plant diseases, yet traditional diagnostic methods such as visual inspections, serological tests, and molecular assays face limitations in sensitivity, specificity, and scalability. In recent years, advancements in diagnostic and surveillance technologies have revolutionized plant health management. Next-Generation Sequencing (NGS) enables comprehensive pathogen profiling, while CRISPR-based diagnostics offer rapid and highly specific detection. Similarly, biosensors and portable devices provide on-site diagnostics, and machine learning and AI applications enhance the analysis of complex datasets, supporting automated disease identification and predictive modeling. Concurrently, advances in disease surveillance through remote sensing technologies, including satellites and Unmanned Aerial Vehicles (UAVs), enable large-scale, real-time monitoring of crop health, detecting disease outbreaks and facilitating targeted interventions. Integrating these diverse technologies into multi-platform systems offers a holistic approach to plant disease management, combining molecular diagnostics, environmental monitoring, and digital platforms to support data-driven decision-making. Several challenges remain, including high costs, technical complexities, and the need for standardized data integration. Addressing these barriers is essential to ensure that these technologies are accessible and effective across various agricultural systems, particularly in resource-limited settings. Future research should focus on enhancing the robustness, affordability, and scalability of these tools while promoting interdisciplinary collaborations.

Keywords: Plant diseases; diagnostics; CRISPR; remote sensing; biosensors.

1. INTRODUCTION

1.1 Plant Disease Management

Plant diseases pose a major threat to global food security and agricultural sustainability, affecting crop yields and quality across various agroecosystems [1]. According to the Food and Agriculture Organization, plant pathogens and pests cause up to 40% of annual crop losses globally, leading to economic losses exceeding $220 billion annually. Diseases such as rusts, blights, mildews, and wilts have historically caused severe agricultural damage, sometimes resulting in famines, such as the Irish Potato Famine caused by *Phytophthora infestans* in the mid-19th century. Modern agriculture has implemented various strategies for managing plant diseases, including crop rotation, chemical treatments, and the development of resistant crop varieties [2]. However, the rise of new pathogens and the resurgence of old ones due to climate change, increased international trade, and changes in agricultural practices highlight the need for advanced diagnostic and surveillance tools. Globalization has led to the unintentional spread of invasive pathogens, complicating the management of plant health at a global scale. Effective disease management is crucial not only for ensuring food production but also for maintaining biodiversity and ecosystem stability. In recent years, integrated pest management (IPM) approaches have gained prominence as sustainable disease management strategies, combining cultural, biological, and chemical methods to reduce reliance on pesticides [3]. Such strategies rely heavily on the early and accurate detection of pathogens, which forms the foundation for disease prevention and control.

1.2 Challenges in Early Disease Detection

Early detection of plant diseases is a critical component of effective disease management, enabling timely intervention and reducing the spread of infections. Traditional methods for detecting plant pathogens, including visual inspections and laboratory-based assays, are time-consuming and require specialized expertise. These conventional techniques often fail to detect pathogens in their latent stages or at low infection levels, leading to delayed response and increased disease impact. Visual inspections, while cost-effective and widely used, are inherently subjective and can be influenced by environmental factors and the inspector's experience [4]. Serological methods, such as enzyme-linked immunosorbent assays (ELISA), offer higher specificity but may suffer from cross-reactivity and are not suitable for detecting novel or rapidly evolving pathogens. Molecular techniques, such as polymerase chain reaction (PCR), have become the gold standard for pathogen detection due to their high sensitivity and specificity; however, they are limited by high costs, the need for specialized equipment, and the potential for contamination. In recent years, the development of next-generation sequencing (NGS) technologies has revolutionized pathogen detection by enabling high-throughput screening of complex samples and the identification of previously unknown pathogens [5]. However, these advanced techniques require significant computational resources and bioinformatics expertise, which may limit their adoption in routine diagnostics. Similarly, the integration of remote sensing and machine learning for early disease surveillance is promising but still faces challenges related to data interpretation, sensor calibration, and the high costs of deployment.

1.3 Objective and Scope of the Review

Given the critical importance of accurate and timely detection for plant disease management, this review aims to provide a comprehensive overview of recent advances in plant disease diagnostics and surveillance. The objective is to highlight emerging technologies that address the limitations of traditional diagnostic methods, such as delayed detection and lack of sensitivity, and to explore novel approaches that integrate diagnostics with real-time disease monitoring. Specifically, this review will focus on cutting-edge developments in molecular diagnostics, such as CRISPR-based assays, biosensors, and portable devices, as well as advancements in disease surveillance using remote sensing and digital platforms [6]. We will also discuss the potential of integrating multi-technology platforms to create holistic disease management systems that offer predictive capabilities. The review will critically evaluate the strengths and weaknesses of these technologies, considering factors such as cost, accessibility, and practical implementation in diverse agricultural settings. By synthesizing recent research findings and technological innovations, this review aims to provide researchers, policymakers, and practitioners with a deeper understanding of the current landscape of plant disease diagnostics and surveillance, ultimately guiding the development of more effective and sustainable disease management strategies. The scope of this review encompasses both laboratory-based and field-deployable technologies, with a particular emphasis on innovations that facilitate rapid, sensitive, and specific pathogen detection. We will also consider the challenges associated with adopting these technologies in resource-limited settings and propose future directions for research and development [7].

2. TRADITIONAL PLANT DISEASE DIAGNOSTICS

2.1 Visual Inspections and Field Surveys

Visual inspections and field surveys are the oldest and most commonly used methods for diagnosing plant diseases, often serving as the first line of defense in disease detection and management. These techniques rely on identifying symptomatic changes in plants, such as discoloration, wilting, necrosis, or abnormal growth patterns, which are indicative of disease presence. Trained agronomists or plant pathologists conduct these assessments, looking for morphological symptoms specific to certain pathogens. For example, the presence of "rust pustules" on wheat leaves suggests infection by *Puccinia spp.*, while "blackleg" symptoms on canola indicate *Leptosphaeria maculans* infection [8]. Visual inspections are inherently subjective, and their accuracy depends significantly on the experience and expertise of the observer. Additionally, visual symptoms often manifest only at later stages of infection, making early detection challenging. Moreover, environmental factors, such as nutrient deficiencies, drought stress, or insect damage, can produce symptoms similar to those caused by pathogens, leading to misdiagnosis [9]. The complexity of visual assessments is further compounded when multiple pathogens co-infect the same host, resulting in overlapping or atypical symptoms. To overcome some of these limitations, visual inspections are often complemented by digital tools, such as smartphone apps and image analysis software, which can improve the consistency and accuracy of disease identification. For instance, deep learning algorithms have been successfully applied to detect foliar diseases in crops such as wheat, rice, and tomato, achieving high classification accuracies in controlled settings. Nonetheless, field deployment of these technologies remains limited due to the need for large, annotated datasets and potential challenges in distinguishing between biotic and abiotic stress factors [10].

2.2 Serological Techniques (e.g., ELISA)

Serological techniques are widely used for the detection of plant pathogens, particularly viruses, due to their ability to specifically recognize pathogen antigens using antibodies. Enzyme-linked immunosorbent assay (ELISA) is the most commonly used serological method and has been a standard diagnostic tool in plant pathology for decades. In ELISA, pathogen-specific antibodies are used to capture and detect antigens from infected plant tissues, providing a sensitive and relatively straightforward means of disease identification [11]. One of the main advantages of ELISA is its versatility and ease of use. It can be adapted for high-throughput screening, making it suitable for large-scale surveys. ELISA has been successfully used to detect a wide range of plant pathogens, including viruses (e.g., Tomato mosaic virus), bacteria (e.g., *Pseudomonas syringae*), and fungi (e.g., *Verticillium spp.*). In addition, various ELISA formats, such as direct, indirect, and sandwich ELISA, have been developed to improve sensitivity and specificity depending on the target pathogen and the availability of antibodies [12]. Despite its widespread use, ELISA has several limitations. The primary drawback is its reliance on the availability of pathogen-specific antibodies, which may not exist for newly emerging pathogens or those with high genetic variability. Moreover, serological cross-reactivity can occur, leading to false positives, especially in complex samples containing multiple closely related pathogens. ELISA also has a relatively low sensitivity compared to molecular techniques such as PCR, making it less effective for detecting pathogens at low concentrations. To address these limitations, several variations of ELISA, such as the double-antibody sandwich ELISA (DAS-ELISA) and the recombinant antibody-based ELISA, have been developed to enhance detection specificity [13]. Additionally, lateral flow immunoassays (LFAs) have emerged as a more user-friendly, field-deployable format of serological detection, providing rapid results without the need for specialized equipment. However, LFAs typically exhibit lower sensitivity compared to standard ELISA, limiting their use in detecting pathogens at low infection levels.

2.3 Molecular Methods (PCR and Variants)

Molecular techniques, particularly polymerase chain reaction (PCR) and its variants, have become the gold standard for plant disease diagnostics due to their high sensitivity, specificity, and versatility. PCR amplifies specific DNA or RNA sequences of the pathogen, enabling detection even at very low concentrations, which is critical for early diagnosis [14]. Conventional PCR has been widely used for pathogen identification in numerous crops, detecting pathogens such as *Fusarium spp.* in cereals and *Ralstonia solanacearum* in solanaceous crops. Real-time quantitative PCR (qPCR) represents a significant advancement over conventional PCR, allowing for both detection and quantification of pathogen DNA in real-time through the use of fluorescent dyes or probes. qPCR has been used extensively for the detection of soilborne pathogens such as *Verticillium dahliae* and *Phytophthora spp.*, providing quantitative data that can inform disease severity and guide management decisions. Another key variant, reverse transcription PCR (RT-PCR), is used to detect RNA viruses by first converting viral RNA into complementary DNA (cDNA) before amplification, making it invaluable for the diagnosis of viral diseases such as Tobacco mosaic virus and Cucumber mosaic virus [15]. Despite their advantages, PCR-based methods have limitations, including the need for specialized equipment, high costs, and the potential for contamination due to the high sensitivity of the technique. Additionally, PCR requires prior knowledge of the pathogen's genetic sequences, which restricts its applicability for detecting unknown or newly emerging pathogens. To overcome these challenges, several PCR variants have been developed, such as multiplex PCR, which allows simultaneous detection of multiple pathogens in a single reaction, and digital PCR, which offers even higher sensitivity and precision [16]. Recently, isothermal amplification methods, such as loop-mediated isothermal amplification (LAMP), have emerged as powerful alternatives to traditional PCR. LAMP can amplify DNA at a constant temperature, eliminating the need for thermal cycling and reducing equipment requirements. This makes LAMP particularly suitable for field diagnostics, as it can be performed using portable devices and produces results in under an hour. Moreover, LAMP's high sensitivity and specificity have been demonstrated for a range of pathogens, including *Xanthomonas oryzae* in rice and *Phytophthora infestans* in potatoes [17].

3. EMERGING DIAGNOSTIC TECHNOLOGIES

3.1 Next-Generation Sequencing (NGS)

Next-Generation Sequencing (NGS) has revolutionized plant disease diagnostics by enabling comprehensive pathogen detection and characterization at an unprecedented scale and resolution (Table 1). Unlike traditional methods that target specific pathogen DNA or RNA sequences, NGS allows for high-throughput sequencing of entire genomes or transcriptomes, making it ideal for detecting multiple pathogens, identifying novel pathogens, and understanding complex host-pathogen interactions. NGS techniques, such as Illumina sequencing, nanopore sequencing, and PacBio sequencing, have been used to profile microbial communities, identify latent infections, and track pathogen evolution and resistance mechanisms [18]. One of the key advantages of NGS is its ability to perform metagenomic analysis, where all genetic material within a sample is sequenced without prior knowledge of the pathogen. This unbiased approach has been instrumental in identifying new and emerging pathogens, such as *Tomato brown rugose fruit virus* and novel strains of *Xanthomonas spp*. For example, metagenomic NGS successfully identified the causal agent of a novel disease affecting watermelon crops, providing critical insights into its epidemiology and guiding management practices [19]. NGS enables the detection of co-infections, which are often missed by conventional methods, and can reveal complex pathogen interactions that influence disease outcomes. Despite its transformative potential, NGS has several limitations that hinder its widespread adoption in routine diagnostics. High costs, the need for specialized equipment and bioinformatics expertise, and complex data interpretation are major challenges. Moreover, the detection sensitivity of NGS depends on sequencing depth and sample quality, which can vary significantly across different plant tissues and environmental conditions. To address these issues, new strategies such as targeted NGS (amplicon sequencing) and hybridization-based enrichment techniques have been developed to increase sensitivity and reduce sequencing costs [20]. Additionally, portable NGS platforms like the Oxford Nanopore MinION have emerged, allowing for real-time, field-based sequencing and on-site pathogen detection [21].

3.2 CRISPR-Based Detection

CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) technology has emerged as a powerful tool for precise and rapid pathogen detection in plant disease diagnostics (Fig. 1). CRISPR-based methods leverage the specificity of CRISPR-associated proteins (e.g., Cas9, Cas12, Cas13) to identify pathogen DNA or RNA sequences, providing highly sensitive and specific detection. One of the most promising applications of CRISPR in diagnostics is the SHERLOCK (Specific High Sensitivity Enzymatic Reporter Unlocking) and DETECTR (DNA Endonuclease-Targeted CRISPR Trans Reporter) platforms, which use Cas13 and Cas12 enzymes, respectively, to target specific nucleic acid sequences and produce a detectable signal [22]. The CRISPR-Cas system's programmability allows for the rapid development of assays targeting virtually any pathogen, including bacteria, fungi, and viruses. For example, CRISPR-Cas12a has been successfully used to detect *Tomato yellow leaf curl virus* in infected tomato plants within 30 minutes, demonstrating its potential as a point-of-care diagnostic tool. Similarly, CRISPR-Cas13 has been applied to detect RNA viruses such as *Potato virus Y* and *Cucumber mosaic virus*, offering high sensitivity and specificity without the need for complex instrumentation [23]. One of the key advantages of CRISPR-based diagnostics is their adaptability to field conditions. CRISPR assays can be integrated into lateral flow devices, similar to pregnancy test strips, making them highly suitable for on-site, rapid pathogen detection. Moreover, CRISPR diagnostics do not require thermal cycling, unlike PCR, and can be performed using simple isothermal amplification methods, reducing equipment requirements. However, challenges such as potential off-target effects, the need for optimized guide RNA design, and the scalability of CRISPR-based platforms must be addressed to fully realize their potential in plant disease diagnostics [24].

3.3 Biosensors and Portable Devices

Biosensors are analytical devices that combine a biological recognition element with a transducer to detect specific pathogens or biomolecules. In plant disease diagnostics, biosensors can detect pathogen-derived molecules such as proteins, nucleic acids, or volatile organic compounds (VOCs), offering rapid and sensitive detection. Depending on the transducer type, biosensors can be categorized into electrochemical, optical, and piezoelectric sensors, each with distinct advantages and limitations. Electrochemical biosensors are among the most widely used for plant pathogen detection due to their high sensitivity, low cost, and ability to be miniaturized into portable devices [25]. For instance, an electrochemical DNA biosensor was developed for the detection of *Phytophthora infestans*, the causative agent of late blight in potatoes, achieving high sensitivity and specificity in field samples. Similarly, paper-based electrochemical biosensors have been used to detect *Ralstonia solanacearum* in tomato plants, demonstrating the feasibility of low-cost, disposable diagnostic devices for use in remote areas [26]. Optical biosensors, which rely on changes in light properties such as fluorescence, absorbance, or surface plasmon resonance (SPR), have also been applied in plant disease diagnostics. A SPR-based biosensor was used to detect *Potato virus X* in potato leaves, providing real-time, label-free detection with high specificity. Additionally, portable optical devices such as smartphone-based fluorescence readers have been developed, enabling point-of-care diagnostics with minimal equipment. Despite their potential, biosensors face several challenges, including limited shelf-life of biological components, susceptibility to environmental interference, and the need for extensive validation in diverse field conditions [27]. Recent advances in synthetic biology and nanotechnology, such as the development of synthetic receptors and nanomaterial-based transducers, are addressing these limitations, paving the way for more robust and versatile biosensing platforms.

3.4 Machine Learning and AI Applications

Machine learning (ML) and artificial intelligence (AI) have emerged as powerful tools for plant disease diagnostics, particularly in the analysis of complex data such as images, genetic sequences, and sensor outputs. Image-based ML approaches have been widely used for automated disease detection in crops, leveraging convolutional neural networks (CNNs) to classify disease symptoms from digital images. For instance, CNN models trained on large datasets of plant leaf images achieved over 95% accuracy in identifying diseases in crops such as wheat, rice, and cassava [28]. Beyond image analysis, AI algorithms are being integrated into remote sensing and IoT (Internet of Things) platforms for large-scale disease surveillance. For example, deep learning models have been used to analyze drone and satellite imagery to detect early signs of disease stress in vineyards and wheat fields, providing valuable insights into disease spread and severity. AI-powered predictive models have been developed to forecast disease outbreaks based on environmental conditions, pathogen genetics, and host susceptibility [29]. While AI offers significant promise for improving the accuracy and scalability of plant disease diagnostics, several challenges remain. These include the need for large, high-quality datasets for training, the potential for bias and overfitting, and the difficulty in interpreting complex models.

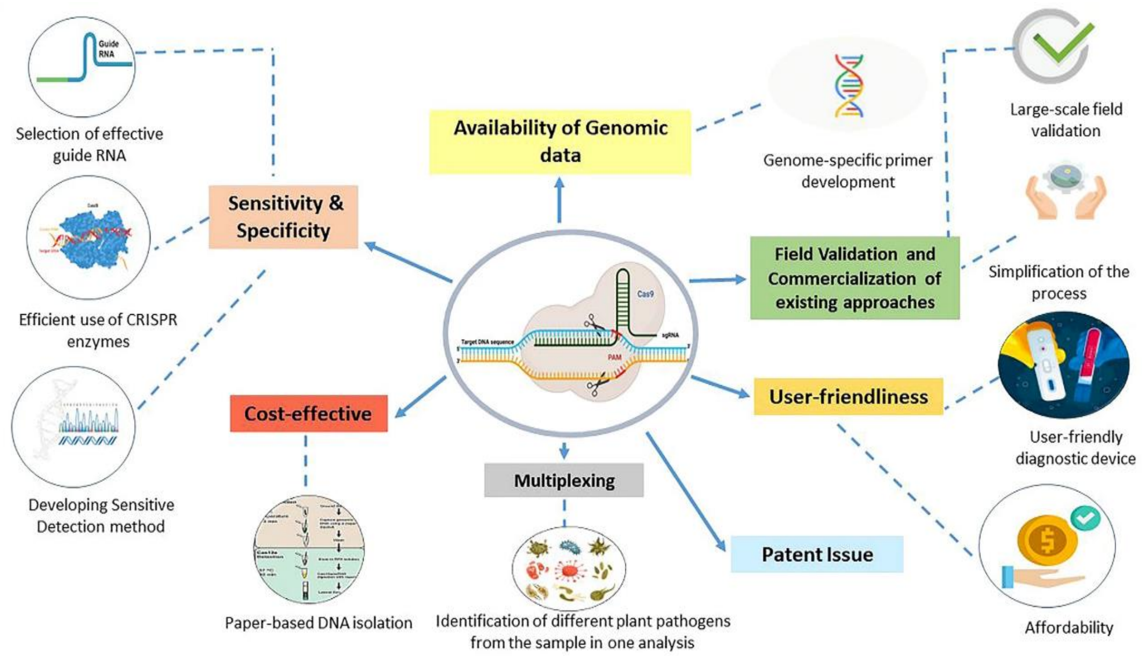

Fig. 1. Challenges associated with CRISPR-based diagnostic methods in agriculture

Table 1. Emerging Diagnostic Technologies in Plant Disease Diagnostics

Diagnostic Technology	Principle	Key Features	Applications in Plant Disease Detection
Loop-Mediated Isothermal Amplification (LAMP)	Amplifies specific DNA sequences at a constant temperature without the need for thermal cycling	Rapid, sensitive, and specific; can be performed on-site without complex equipment	Detection of bacterial, viral, and fungal pathogens in field conditions; suitable for crops like tomato, potato, and rice
CRISPR-based Diagnostics	Utilizes CRISPR-Cas systems to detect specific nucleic acid sequences related to plant pathogens	Ultra-sensitive, programmable, and adaptable to different pathogens	Detection of viruses, bacteria, and fungi in crops such as soybean, wheat, and maize
Next-Generation Sequencing (NGS)	High-throughput sequencing that allows for the identification of entire microbial communities and novel pathogens	Unbiased pathogen detection, discovery of novel species, and deep resolution of pathogen populations	Comprehensive diagnostics for diseases in fruit crops, cereals, and vegetables; useful in research and breeding programs
Quantitative PCR (qPCR)	Amplifies and quantifies pathogen DNA or RNA in real-time using fluorescent dyes	High sensitivity and specificity; allows quantification of pathogen load	Detection of latent infections in crops such as citrus, grapevine, and sugarcane; used for quarantine and certification purposes
ELISA (Enzyme-Linked Immunosorbent Assay)	Uses antibodies to detect specific proteins or antigens produced by pathogens	Reliable, cost-effective, and easy to perform in laboratory settings	Detection of viral, bacterial, and fungal diseases in crops like cucumber, papaya, and tomato
Biosensor-based Diagnostics	Detects pathogens using biological molecules such as enzymes, antibodies, or nucleic acids, coupled with a transducer	Rapid, on-site, and real-time pathogen detection	Detection of bacterial and fungal pathogens in crops like wheat, lettuce, and citrus
Surface Plasmon Resonance (SPR)	Measures changes in refractive index near a sensor surface to detect molecular interactions between pathogens and host molecules	Label-free, real-time, and highly sensitive	Detection of viral and bacterial plant pathogens such as *Xanthomonas* and *Tobamovirus* in various crops
Microfluidics-based Devices	Miniaturized lab-on-a-chip systems that integrate multiple diagnostic steps, such as sample preparation, pathogen detection, and data analysis	Low sample volume, rapid processing, and field deployable	Detection of multiple pathogens in crops like rice, corn, and tobacco simultaneously
Isothermal Recombinase Polymerase Amplification (RPA)	Amplifies DNA or RNA at a constant, low temperature using recombinase enzymes	Simple, fast, and portable; can be performed in resource-limited settings	On-site detection of pathogens like *Phytophthora infestans* and *Xanthomonas* in crops such as tomato and banana
Fluorescence In Situ Hybridization (FISH)	Uses fluorescent probes to hybridize with specific nucleic acid sequences within cells, allowing visualization of pathogen presence	Highly specific, can localize pathogen within tissues	Detection of bacterial, fungal, and viral pathogens in plant tissues such as root, leaf, and fruit samples

4. ADVANCES IN PLANT DISEASE SURVEILLANCE

4.1 Remote Sensing (Satellites, Drones)

Remote sensing technologies, which utilize satellites, aircraft, and drones equipped with advanced imaging sensors, have significantly advanced the field of plant disease surveillance by enabling large-scale monitoring of crops with high temporal and spatial resolution (Table 2) [30]. The primary advantage of remote sensing lies in its ability to non-destructively assess plant health and detect early disease symptoms over extensive areas, which is especially useful in large-scale agricultural systems. These technologies rely on capturing reflectance data across various wavelengths, such as visible, near-infrared (NIR), and thermal infrared, to identify changes in plant physiology and structure that are indicative of disease stress. Satellite remote sensing has been widely used for disease surveillance due to its ability to monitor large geographic areas over time. For example, hyperspectral and multispectral satellite data have been successfully used to detect *Fusarium* head blight in wheat and *Cercospora* leaf spot in sugar beet, based on alterations in spectral reflectance patterns [31]. Satellites such as Landsat, Sentinel-2, and WorldView-3 offer high-resolution imaging capabilities that are valuable for distinguishing between healthy and diseased plants at the field scale. The use of vegetation indices, such as the Normalized Difference Vegetation Index (NDVI) and the Red Edge Inflection Point (REIP), has been particularly effective for quantifying disease severity and mapping disease hotspots. Satellite-based disease monitoring has limitations, including low temporal resolution, cloud cover interference, and the inability to capture fine-scale details within individual fields [32]. To address these challenges, drones equipped with high-resolution cameras and sensors are increasingly being used for disease surveillance. Drones provide greater flexibility in terms of spatial resolution and flight scheduling, allowing for targeted surveys of specific fields or regions. For instance, drone-based hyperspectral imaging has been used to detect grapevine leafroll-associated virus and *Xylella fastidiosa* in olive trees, demonstrating its potential for early disease detection and precise management [33].

4.2 Unmanned Aerial Vehicles (UAVs)

Unmanned Aerial Vehicles (UAVs), commonly known as drones, have become a critical tool for precision agriculture, offering unparalleled flexibility and high-resolution data for plant disease surveillance. UAVs can be equipped with a variety of sensors, including RGB cameras, multispectral and hyperspectral imagers, LiDAR, and thermal cameras, to capture detailed information on plant health and disease status. Their ability to fly at low altitudes and maneuver over complex terrain makes them ideal for conducting rapid and targeted surveys in areas that are difficult to access using traditional methods [34]. UAV-based disease surveillance has been applied to detect a wide range of plant diseases, including *Cercospora* leaf spot in sugar beets, *Phytophthora* root rot in citrus, and *Verticillium* wilt in cotton. By capturing high-resolution multispectral or hyperspectral images, UAVs can detect subtle changes in canopy reflectance that are indicative of disease symptoms, such as chlorosis or necrosis, before they become visible to the naked eye. For instance, UAV-based hyperspectral imaging was used to monitor *Verticillium* wilt in olive orchards, achieving early detection of infected trees with high accuracy. Thermal imaging is another valuable UAV-based tool, as it can detect changes in plant temperature caused by reduced transpiration in diseased plants [35]. This approach has been used to detect water stress and disease in grapevines and citrus orchards, enabling early intervention and targeted treatment. In addition to disease detection, UAVs can also be used for precision pesticide application, targeting specific diseased areas and minimizing chemical use. Despite their advantages, UAV-based surveillance faces several challenges, including regulatory restrictions on UAV flights, limited battery life, and data processing complexities.

4.3 Digital Platforms and IoT-Based Systems

The integration of digital platforms and Internet of Things (IoT)-based systems has emerged as a transformative approach for plant disease surveillance, enabling continuous, real-time monitoring and early warning of disease outbreaks [37]. IoT-based systems utilize networks of interconnected sensors deployed in the field to collect environmental and plant health data, such as soil moisture, temperature, humidity, and leaf wetness, which are key factors influencing disease development. These data are transmitted wirelessly to cloud-based platforms, where they are analyzed using advanced algorithms to identify disease risk patterns and

Table 2. Advances in Plant Disease Surveillance

Surveillance Technique	Description	Key Advantages	Applications in Plant Disease Management
Remote Sensing Technologies	Use of satellite imagery, drones, and UAVs to monitor plant health and detect disease outbreaks through spectral imaging	Large-scale monitoring, early detection, and non-invasive	Detection of disease stress in crops like wheat, maize, and rice; identification of disease hotspots in agricultural landscapes
Geographic Information Systems (GIS)	Spatial analysis and mapping of disease outbreaks, integrating various data sources such as weather, crop conditions, and pest populations	Real-time data integration, precise mapping of disease spread	Tracking of plant disease spread patterns, prediction of future outbreaks based on environmental and geographical data
Artificial Intelligence (AI) and Machine Learning	AI-driven algorithms analyze large datasets from images, sensors, and field data to predict disease occurrence and progression	High accuracy, continuous learning, and adaptability to different conditions	Automated identification and classification of diseases based on leaf images or sensor data for crops like tomato, rice, and cotton
Mobile-Based Surveillance Systems	Mobile apps and platforms that allow farmers to upload images of diseased plants for rapid diagnosis and advisory services	Cost-effective, accessible, and user-friendly for smallholders	Real-time diagnosis of plant diseases in remote areas, rapid response to disease outbreaks in crops like banana, potato, and citrus
Unmanned Aerial Vehicles (UAVs)	UAVs equipped with multispectral and thermal cameras to detect subtle changes in plant physiology caused by diseases	High-resolution data collection, flexible deployment	Identification of early-stage diseases in crops such as vineyards, orchards, and cereal fields
Biosensors and Nanotechnology	Use of biosensors and nano-based tools to detect specific pathogens or disease-related biomarkers in real-time	Highly sensitive, rapid, and on-site detection capabilities	Detection of bacterial, viral, and fungal pathogens in crops like soybean, grape, and lettuce
High-Throughput Phenotyping	Automated platforms using image analysis, robotics, and sensors to track disease progression in controlled environments	Speed and accuracy in screening disease resistance in plant varieties	Breeding programs for disease-resistant crops like wheat, barley, and tomato
DNA Barcoding and Molecular Diagnostics	Use of molecular markers, PCR, and DNA sequencing to identify specific pathogens at genetic levels	High specificity, accuracy, and the ability to detect latent infections	Diagnosis of pathogens such as *Phytophthora*, *Fusarium*, and *Pseudomonas* in crops like potatoes, vegetables, and fruits
Wireless Sensor Networks (WSN)	Networks of sensors that continuously monitor environmental conditions conducive to disease outbreaks	Real-time environmental monitoring, predictive capabilities	Early warning systems for diseases in controlled environments like greenhouses or open fields for crops like cucumber and tomato

(Source: [31], [33], [36])

trigger alerts. IoT-based surveillance systems have been successfully implemented in various crops, such as vineyards, wheat, and citrus orchards, to monitor diseases such as powdery mildew, rust, and citrus greening. For example, a network of IoT sensors deployed in a vineyard was used to monitor environmental conditions conducive to powdery mildew, enabling the early detection of outbreaks and the optimization of fungicide applications [38]. An IoT-based system was developed to detect *Phytophthora* blight in chili crops by monitoring soil moisture and temperature, demonstrating its potential for disease risk prediction and management. Digital platforms, such as Plantix, e-Phytopath, and Agdia, have also emerged as valuable tools for disease surveillance, providing farmers and researchers with user-friendly interfaces to report disease symptoms, access diagnostic resources, and receive management recommendations. These platforms often incorporate image recognition algorithms and machine learning models to diagnose diseases from user-uploaded images, offering a cost-effective solution for disease surveillance in remote or resource-limited areas [39]. Plantix uses AI algorithms to diagnose over 30 different crop diseases based on smartphone images, achieving high accuracy and enabling real-time disease reporting across diverse geographic regions. The combination of IoT and digital platforms provides a comprehensive framework for disease surveillance, offering both real-time environmental monitoring and accessible diagnostic tools. However, several challenges remain, including data interoperability, cybersecurity risks, and the need for reliable internet connectivity in rural areas [40]. To address these issues, recent research has focused on developing low-power, long-range IoT networks, such as LoRaWAN and NB-IoT, and enhancing data security through blockchain technology.

5. INTEGRATION OF DIAGNOSTICS AND SURVEILLANCE

5.1 Multi-Technology Platforms

Integrating multiple diagnostic and surveillance technologies is crucial for enhancing the precision and reliability of plant disease management. Multi-technology platforms combine traditional diagnostic tools, such as PCR and ELISA, with emerging techniques like biosensors, CRISPR-based assays, and remote sensing, to create a comprehensive framework for disease detection and monitoring [41]. Such integrated systems provide a more holistic view of plant health by capturing a diverse array of data from various sources, ranging from molecular signals to physiological and environmental parameters. For example, a multi-technology platform might use molecular diagnostics for pathogen identification at the field level, while simultaneously deploying remote sensing and UAVs for large-scale disease surveillance and early detection of disease hotspots. One prominent application of multi-technology platforms is in precision agriculture, where diagnostic data are integrated with real-time environmental monitoring systems and remote sensing data to inform disease management decisions. For instance, a platform combining CRISPR-based diagnostics and UAV imagery was successfully used to detect and monitor *Xylella fastidiosa* infections in olive orchards, enabling rapid response and targeted management strategies [42]. Another example is the integration of NGS with biosensors and cloud-based data analytics, which allows for real-time tracking of pathogen spread and the identification of disease variants in the field. Incorporating machine learning algorithms and artificial intelligence (AI) into these platforms further enhances their capabilities by enabling automated analysis of large datasets and the identification of complex patterns that may not be apparent through traditional methods. AI models can process diverse data inputs, such as genomic sequences, environmental variables, and remote sensing imagery, to generate predictive models and disease risk maps, providing actionable insights for disease management. For example, a multi-technology platform that integrated machine learning models with sensor networks and drone imagery was used to predict the onset of wheat rust and downy mildew in vineyards, demonstrating its utility in precision disease forecasting [43].

5.2 Predictive Modeling and Disease Forecasting

Predictive modeling and disease forecasting are essential components of integrated plant disease management systems, enabling proactive measures to prevent disease outbreaks and optimize crop health [44]. Predictive models use historical data, real-time environmental conditions, and pathogen epidemiology to forecast disease incidence, severity, and spread. These models often incorporate statistical and machine learning techniques to account for complex interactions between host, pathogen, and environment, providing early warnings and guiding management decisions. One of the most widely used predictive modeling frameworks is the disease triangle model, which considers the interactions between the host plant, pathogen, and environmental conditions to assess disease risk. Modern disease forecasting systems build on this framework by incorporating additional variables such as genetic resistance, crop management practices, and landscape-level factors, enhancing their predictive power [45]. For example, the DSSAT (Decision Support System for Agrotechnology Transfer) model integrates plant growth, disease, and weather models to predict disease outcomes for crops like wheat and maize under different management scenarios. Machine learning and AI have revolutionized predictive modeling by enabling the development of dynamic, data-driven models that can learn from real-time data inputs and continuously update disease forecasts. Deep learning models have been used to predict disease outbreaks based on weather patterns and satellite imagery, achieving high accuracy in forecasting diseases such as soybean rust and powdery mildew. Similarly, AI-based models have been used to predict the spread of *Phytophthora infestans*, the causative agent of late blight in potatoes, allowing for optimized fungicide application and reduced disease impact [46]. Despite their potential, predictive models face several challenges, including the need for high-quality, comprehensive datasets and the difficulty of accounting for the complex, non-linear interactions that drive disease dynamics. Recent efforts have focused on integrating diverse data sources, such as genomic data, phenotypic observations, and remote sensing imagery, to create more robust models capable of capturing these complexities [47].

6. CHALLENGES

6.1 Technical and Practical Limitations

While emerging technologies have greatly improved plant disease diagnostics and surveillance, several technical and practical limitations hinder their widespread adoption. One major challenge is the sensitivity and specificity of new diagnostic tools, which can vary depending on the pathogen, host, and environmental conditions. For example, molecular techniques like PCR are highly sensitive but can suffer from false positives due to cross-contamination or non-specific amplification [48]. Remote sensing techniques are susceptible to interference from environmental factors such as soil background, canopy structure, and lighting conditions, which can complicate data interpretation. Another technical limitation is the lack of interoperability and data integration between different diagnostic and surveillance platform. Many existing systems are designed for specific crops or pathogens, making it difficult to apply them in diverse agricultural settings. Additionally, complex data processing and interpretation often require specialized expertise, limiting the use of advanced technologies by non-expert users [49].

6.2 Cost and Accessibility Issues

The high costs associated with advanced diagnostic and surveillance technologies pose a significant barrier to their adoption, particularly in resource-limited regions. Technologies such as NGS, UAVs, and advanced biosensors require substantial investment in equipment, infrastructure, and technical expertise, making them inaccessible to many smallholder farmers. The maintenance and operational costs of these systems can be prohibitive, limiting their scalability and long-term sustainability [50]. To address these issues, low-cost alternatives such as portable PCR devices, paper-based biosensors, and smartphone-based diagnostic tools have been developed, but their sensitivity and robustness under field conditions often lag behind more sophisticated technologies. Bridging this gap between cost and performance is a key challenge for future research and development.

7. FUTURE AND RECOMMENDATIONS

The future of plant disease diagnostics and surveillance will likely involve the integration of advanced technologies with scalable, low-cost solutions that are accessible to farmers worldwide [51]. One promising trend is the development of hybrid platforms that combine multiple diagnostic methods, such as CRISPR-based assays with portable NGS devices, to achieve high sensitivity and specificity at a lower cost. Another trend is the increasing use of AI and machine learning to automate data analysis and provide user-friendly interfaces that can be used by non-experts. Future research should focus on enhancing the robustness and scalability of these technologies, developing standardized data formats and interoperability protocols to facilitate data integration, and ensuring that new tools are validated under diverse field conditions [52].

8. CONCLUSION

Recent advances in plant disease diagnostics and surveillance, including multi-technology platforms, remote sensing, CRISPR-based detection, and AI-driven predictive models, have greatly enhanced our ability to detect and manage plant diseases with higher precision and efficiency. These technologies address the limitations of traditional methods, providing rapid, sensitive, and large-scale monitoring capabilities. Challenges such as high costs, technical complexity, and limited accessibility, particularly in resource-constrained regions, remain significant barriers to widespread adoption. Integrating these tools into comprehensive, cost-effective platforms and ensuring interoperability will be critical for future progress. Collaborative efforts between researchers, industry, and policymakers are needed to develop robust, scalable solutions that can be effectively deployed globally, ultimately supporting sustainable agriculture and improving global food security.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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