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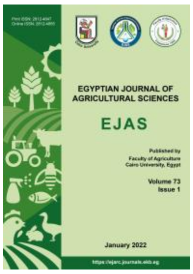

Plant Diseases: Types, Causes and Impacts

By
Abdelhak Rhouma

Regional Centre of Agricultural Research of Sidi Bouzid, Gafsa Road Km 6, B.P. 357, 9100 Sidi Bouzid, Tunisia

ABSTRACT

Plant diseases pose a significant threat to global agriculture, food security, and environmental sustainability, causing substantial economic losses and ecological disruptions. This review paper provides a comprehensive overview of the major types of plant diseases, their causative agents, and the complex interplay of factors that influence their development and spread. Fungal, bacterial, viral, nematode, and other microbial pathogens are examined in detail, highlighting their unique characteristics, modes of infection, and the challenges they present to disease management. The economic impacts of plant diseases are profound, with annual global crop losses estimated at billions of dollars, threatening the livelihoods of millions of farmers and exacerbating food insecurity, particularly in vulnerable regions. Historical examples, such as the Irish Potato Famine and the ongoing threat of Panama disease, underscore the devastating consequences of unchecked plant diseases. Ecologically, plant diseases disrupt ecosystems, reduce biodiversity, and alter ecosystem functions, as seen in the near-extinction of the American chestnut due to chestnut blight and the spread of sudden oak death in North American forests. The social consequences of plant diseases are equally significant, contributing to poverty, migration, and food shortages, particularly in developing countries where agriculture is a primary source of income and nutrition. The review also explores current and emerging strategies for managing plant diseases, emphasizing the importance of integrated and sustainable approaches. Biological control, cultural practices, chemical treatments, and genetic engineering are discussed as key components of effective disease management. Emerging technologies, such as remote sensing, artificial intelligence, nanotechnology, and microbiome engineering, offer innovative solutions for early detection, targeted control, and enhanced plant resilience. The paper concludes by highlighting the need for global collaboration, research, and policy support to address the evolving challenges posed by plant diseases. By integrating scientific innovation, sustainable practices, and inclusive policies, we can mitigate the impact of plant diseases, protect ecosystems, and ensure food security for future generations. This review underscores the critical importance of plant disease management in building resilient agricultural systems and promoting environmental and social well-being in the face of global challenges.

Keywords: *environmental conditions, effects of plant diseases, types of plant diseases, plant disease management, crop diseases.*

1. INTRODUCTION

Plants are the cornerstone of life on Earth, serving as the primary producers in ecosystems and playing a critical role in sustaining human civilization (Gao *et al.*, 2024). They provide food, fiber, fuel, and medicine, while also contributing to environmental stability through carbon sequestration, soil conservation, and

*Corresponding author: E. mail : abdelhak.rhouma@gmail.com

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water regulation (Chen *et al.,* 2022). However, the health and productivity of plants are constantly threatened by a myriad of diseases caused by pathogens such as fungi, bacteria, viruses, nematodes, and other microorganisms (Liu *et al.,* 2022). Plant diseases have been a persistent challenge throughout human history, with devastating consequences for agriculture, economies, and societies (Tahat *et al.,* 2020). Historical examples, such as the Irish Potato Famine of the 1840s caused by the oomycete *Phytophthora infestans*, underscore the profound impact of plant diseases on food security and human welfare (Telo da Gama, 2023). More recently, outbreaks like the wheat stem rust epidemic in East Africa and the global spread of Panama disease in banana plantations highlight the ongoing vulnerability of crops to emerging and re-emerging pathogens (Fernando, 2012; Šola *et al.,* 2025).

The study of plant diseases, known as plant pathology, is essential for understanding the complex interactions between pathogens, plants, and the environment (Kubiak *et al.,* 2017; Angelotti *et al.,* 2024). Plant diseases are not merely the result of pathogen activity but are influenced by a combination of factors, including host susceptibility, environmental conditions, and human practices (Lahlali *et al.,* 2022). For instance, the intensification of agriculture, characterized by monoculture and excessive use of chemical inputs, has created favorable conditions for the proliferation of pathogens (He *et al.,* 2021). Similarly, global trade and climate change have facilitated the spread of diseases to new regions, where they can cause significant damage due to the lack of natural resistance in local plant populations (Prospero and Cleary, 2017; Ye *et al.,* 2024). The economic impact of plant diseases is staggering, with annual global crop losses estimated at billions of dollars, threatening the livelihoods of millions of farmers and exacerbating food insecurity in vulnerable regions (Gai and Wang, 2024; Jiménez-Hernández *et al.,* 2024).

Beyond their economic consequences, plant diseases also pose significant ecological challenges (Vega and Martínez, 2023). They can disrupt ecosystems by reducing biodiversity, altering species composition, and weakening plant communities (González-Rodríguez *et al.,* 2024). For example, the introduction of chestnut blight in North America led to the near-extinction of the American chestnut, a keystone species that played a vital role in forest ecosystems (Cobb and Metz, 2017; Danti *et al.,* 2017; Garbelotto and Gonthier, 2017). Furthermore, the management of plant diseases often relies on chemical pesticides, which can have unintended consequences for non-target organisms, soil health, and water quality (Lione *et al.,* 2017). As such, there is an urgent need for sustainable and integrated approaches to plant disease management that balance productivity with environmental stewardship (Ploetz *et al.,* 2017).

This review paper aims to provide a comprehensive overview of plant diseases, encompassing their causes, impacts, and management strategies. We begin by categorizing the major types of plant diseases and their causative agents, followed by an exploration of the factors that influence their development and spread. We then discuss the economic and ecological consequences of plant diseases, highlighting their far-reaching implications for food security and environmental sustainability. Finally, we examine current and emerging strategies for managing plant diseases, emphasizing the importance of innovation, collaboration, and sustainability in addressing this global challenge. By synthesizing existing knowledge and identifying future research directions, this paper seeks to contribute to the ongoing efforts to mitigate the impact of plant diseases and ensure the resilience of agricultural systems in the face of evolving threats.

2. Types of Plant Diseases

The journey to understand the microscopic world and its role in disease, particularly in plant pathology, is a testament to the persistent curiosity of early scientists. While ancient texts acknowledged plant ailments, the true causal agents remained a mystery until the advent of microscopy and the refinement of experimental methods (Degani, 2025).

The earliest glimpses into the microbial world came from Antonie van Leeuwenhoek in the late 17^{th} century, who, using his self-made microscopes, was the first to observe "animalcules," now known as bacteria, though their connection to disease was not yet fully understood. Over a century later, in the early 19^{th} century, Agostino Bassi (often considered a precursor to Louis Pasteur) made a pivotal discovery regarding fungi; he demonstrated that a living, microscopic fungus, later named

Beauveria bassiana in his honor, caused the muscardine disease of silkworms marking one of the first clear associations between a specific microorganism and a disease. This laid groundwork for the broader acceptance of the germ theory ((Abdelrhim *et al.,* 2023; Rodríguez-Vázquez *et al.,* 2023; Wang, 2023; Zhou *et al.,* 2024).

The bacterial world revealed itself further with Louis Pasteur and Robert Koch. Pasteur's groundbreaking work in the mid-19th century disproved spontaneous generation and solidified the "germ theory of disease," demonstrating that microorganisms cause fermentation and spoilage, which was then extended to human and animal diseases. Koch, a contemporary of Pasteur, provided definitive proof of the bacterial etiology of diseases through his famous postulates, which provided a systematic framework for linking specific microbes to specific diseases. In plant pathology, Thomas J. Burrill made a significant breakthrough in 1878 when he identified bacteria as the cause of fire blight in pear and apple trees, an observation confirmed by Erwin Frink Smith who spent his career meticulously documenting bacterial plant diseases, overcoming initial skepticism about bacteria as plant pathogens (Rentschler *et al.,* 2021; Monteiro *et al.,* 2022; Adedibu *et al.,* 2024; Hu *et al.,* 2024; Yu *et al.,* 2024).

The discovery of viruses presented a new challenge, as these agents were too small to be seen with early microscopes. In the late 19th century, working independently on tobacco mosaic disease, Adolf Mayer showed the disease was transmissible through sap, suggesting a soluble infectious agent. Following this, in 1892, Dmitri Ivanovsky demonstrated that the causative agent of tobacco mosaic disease could pass through porcelain filters that retained bacteria, indicating an even smaller infectious entity. Later, in 1898, Martinus Beijerinck independently confirmed Ivanovsky's filtration experiments and coined the term "virus" (from the Latin for "poison") to describe this "contagium vivum fluidum" (contagious living fluid) that could only reproduce within living cells, effectively founding the field of virology (Ranawaka *et al.,* 2020; Jones, 2021; Chen *et al.,* 2023; Devi *et al.,* 2024).

Further, into the 20th century, other classes of pathogens were identified. The existence of nematodes as plant pathogens was recognized much earlier, with observations of their presence in diseased plants dating back to the 18th century, but their definitive role as causal agents and widespread impact became clearer with dedicated research in the late 19th and early 20th centuries, as the field of nematology emerged (Akinsanya *et al.,* 2020; Rusinque *et al.,* 2021; Rahman *et al.,* 2023; Meresa *et al.,* 2024). The discovery of phytoplasmas (initially called mycoplasma-like organisms) came in the late 1960s, specifically in 1967 by Japanese scientists Doi, who found these wall-less prokaryotes in the phloem of plants suffering from diseases like aster yellows, distinguishing them from bacteria and fungi (Kaponi *et al.,* 2024; Zhang *et al.,* 2024; Ferretti and Taglienti, 2025). Finally, viroids, representing an even simpler form of pathogen, were first identified by Theodor Otto Diener in 1971, when he discovered the potato spindle tuber viroid (PSTVd) as a small, circular, single-stranded RNA molecule lacking a protein coat, marking the recognition of a fundamentally new category of infectious agent. These early discoveries laid the foundation for modern plant pathology, transforming our understanding of plant diseases from mysterious ailments to explainable biological phenomena, paving the way for effective disease management strategies (Abd-Elgawad, 2021; Lahlali *et al.,* 2022; Wang, 2023; Devi *et al.,* 2024; Degani, 2025).

Plant diseases are caused by a diverse array of pathogens, each with unique characteristics, life cycles, and modes of infection. These pathogens can be broadly categorized into fungal (Degani, 2025), bacterial (Adedibu *et al.,* 2024), viral, nematode, and other microbial agents, each contributing to the complex landscape of plant disease. Fungal pathogens are among the most common and destructive causes of plant diseases, responsible for a wide range of symptoms, including leaf spots, wilts, rots, and blights (Abdelrhim *et al.,* 2023; McLaughlin *et al.,* 2023; Wang, 2023; Zhou *et al.,* 2024; Degani, 2025). Fungi such as *Phytophthora infestans* (late blight in potatoes) (Velasquez-Vasconez *et al.,* 2024), and *Puccinia graminis* (stem rust in wheat) (Rodríguez-Vázquez *et al.,* 2023), have historically caused catastrophic crop losses (Rodríguez-Vázquez *et al.,* 2023; Srisawad *et al.,* 2023). Fungal diseases often thrive in humid conditions, spreading through spores that can be carried by water, wind, or insects (Abdelrhim *et al.,* 2023; Wang, 2023; Cotter *et al.,* 2024). The adaptability and resilience of fungal pathogens, coupled with their ability to survive in soil or plant debris, make them particularly challenging to control (Abdelrhim *et al.*, 2023; Zhou *et al.,* 2024).

Bacterial diseases, though less numerous than fungal diseases, can be equally devastating (Rentschler *et al.*, 2021). Bacterial pathogens, such as *Xanthomonas* and *Pseudomonas* species, cause diseases like bacterial blight, leaf spots, and cankers (Díaz *et al.,* 2023; Martinez *et al.*, 2025). These pathogens typically enter plants through natural openings or wounds, spreading rapidly within the plant's vascular system and often leading to systemic infections (Vulcanescu *et al.*, 2024). For example, *Xanthomonas oryzae*, the causative agent of bacterial blight in rice, can cause yield losses of up to 50% in severe cases (Adedibu *et al.*, 2024; Hu *et al.*, 2024; Yu *et al.*, 2024). Bacterial diseases are often characterized by symptoms such as water-soaked lesions, wilting, and gummosis, and their management is complicated by the limited availability of effective bactericides and the risk of antibiotic resistance (Monteiro *et al.*, 2022; Adedibu *et al.*, 2024; Spagnolo, 2024).

Viral diseases, caused by plant-infecting viruses, represent another significant category of plant pathogens (Wang *et al.*, 2022). Viruses such as the Tobacco mosaic virus (Ibrahim *et al.*, 2025) and the Tomato yellow leaf curl virus (Yan *et al.,* 2021) are responsible for stunting, mosaic patterns, leaf curling, and other deformities in plants. Unlike fungi and bacteria, viruses are obligate parasites that rely entirely on host cells for replication (Jones, 2021). They are typically transmitted by vectors such as insects, nematodes, or fungi, as well as through mechanical means like contaminated tools or human handling (Dáder *et al.*, 2012; Ranawaka *et al.,* 2020; Chen *et al.*, 2023). Viral diseases are particularly challenging to manage because there are no direct chemical treatments available, and control efforts often focus on preventing transmission through vector management and the use of resistant plant varieties (Devi *et al.,* 2024).

Nematode diseases, caused by microscopic roundworms, primarily affect plant roots, leading to symptoms such as galls, root knots, and stunted growth (Mesa-Valle *et al.,* 2020; Pulavarty *et al.,* 2021; Pun *et al.,* 2024). Root-knot nematodes (*Meloidogyne* spp.) are among the most damaging, infecting a wide range of crops, including tomatoes, potatoes, and soybeans (Akinsanya *et al.,* 2020; Cabianca *et al.,* 2021; Rusinque *et al.,* 2021). These nematodes disrupt the plant's ability to absorb water and nutrients, often resulting in significant yield losses (Akinsanya *et al.,* 2020; Cabianca *et al.,* 2021; Rusinque *et al.,* 2021). Nematode infections are frequently exacerbated by secondary infections from fungi or bacteria, further complicating disease management (Abd-Elgawad, 2021; Rahman *et al.*, 2023; Meresa *et al.,* 2024). Soil-borne nematodes are particularly difficult to control due to their persistence in the soil and the limited availability of effective nematicides (Mendoza-de Gives, 2022).

In addition to these major categories, plant diseases can also be caused by other microbial agents, such as phytoplasmas and viroids (Moelling and Broecker, 2021; Ivanauskas *et al.*, 2024). Phytoplasmas, which are wall-less bacteria, cause diseases like aster yellows and coconut lethal yellowing, often leading to symptoms such as yellowing, stunting, and abnormal growth (Bertaccini, 2021; Wei and Zhao, 2022; Wei *et al.,* 2024). Viroids, which are small, circular RNA molecules, cause diseases like potato spindle tuber viroid, resulting in stunted growth and reduced yields (Ortolá and Daròs, 2023; Kaponi *et al.,* 2024; Zhang *et al.*, 2024). These pathogens are often transmitted by insects or through vegetative propagation, and their management requires careful monitoring and the use of disease-free planting material (Devi *et al.*, 2024; Ferretti and Taglienti, 2025).

Understanding the plant pathogens diversity and their modes of infection is crucial for developing effective disease management strategies (McLaughlin *et al.,* 2023; Devi *et al.*, 2024; Jiménez-Hernández *et al.,* 2024; Degani, 2025). Each type of pathogen presents unique challenges, requiring tailored approaches that consider the biology of the pathogen, the susceptibility of the host, and the environmental conditions that favor disease development (Abd-Elgawad, 2021; Lahlali *et al.*, 2022; Wang, 2023; Devi *et al.,* 2024). By categorizing and studying these pathogens, researchers and farmers can better anticipate and mitigate the risks posed by plant diseases, ultimately contributing to more resilient and sustainable agricultural systems (Abd-Elgawad, 2021; Mendoza-de Gives, 2022; Abdelrhim *et al.*, 2023; Spagnolo, 2024).

3. Causes and Factors Influencing Plant Diseases

Plant diseases are the result of complex interactions between pathogens, host plants, and the environment, often referred to as the "disease triangle" (Mannaa and Seo, 2021). Understanding these interactions is essential for predicting, preventing, and managing plant diseases effectively (Angelotti *et al.*, 2024). At the core of any plant disease is the pathogen, a biological agent capable of causing infection (Gautam *et al.*, 2023). Pathogens such as fungi, bacteria, viruses, nematodes, and other microorganisms have evolved sophisticated mechanisms to invade plant tissues, evade host defenses, and exploit plant resources for their own reproduction and survival (Giesen *et al.*, 2024; Madhushan *et al.*, 2025). For example, fungal pathogens like *Fusarium* spp. and *Botrytis* spp. produce enzymes that break down plant cell walls, allowing them to penetrate and colonize host tissues (De Senna and Lathrop, 2017). Similarly, bacterial pathogens such as *Ralstonia solanacearum* use effector proteins to suppress plant immune responses, enabling them to establish systemic infections (Liu *et al.*, 2023). The virulence and adaptability of these pathogens are key determinants of disease severity and spread **(Fig. 1; Table 1)** (Marđetko *et al.*, 2021; Álvarez *et al.*, 2022).

Accurate diagnosis of plant diseases hinges on recognizing specific symptoms indicative of various pathogen types (Gai and Wang, 2024). Fungal diseases often manifest as wilting, spotting (necrosis), mold, pustules, rot (both wet and dry), and changes in plant growth, such as stunting or excessive growth (hypertrophy/hyperplasia), and mummification of organs (Bhardwaj *et al.*, 2019; Abo-Elyousr *et al.*, 2022; Abdedayem *et al.*, 2023; Cotter *et al.*, 2024; Degani, 2025). Bacterial infections commonly cause vascular wilts, soft rots that macerate tissue, cankers, and leaf spots often surrounded by a yellow halo, with bacterial ooze being a distinct sign (Gusberti *et al.*, 2015; Adedibu *et al.*, 2024; Akila *et al.*, 2024; Hu *et al.*, 2024; Ibrahim *et al.*, 2025). Viral diseases are characterized by symptoms like mosaic patterns on leaves, crinkling, stunting, and overall yellowing (chlorosis), without visible signs of the pathogen itself (Ranawaka *et al.*, 2020; Jones, 2021; Chen *et al.*, 2023; Ferretti and Taglienti, 2025). Nematodes, microscopic roundworms, typically lead to stunting, yellowing, wilting, and reduced, often discolored or abnormally branched, feeder root systems **(Table 1)** (Mesa-Valle *et al.*, 2020; Pulavarty *et al.*, 2021; Mendoza-de Gives, 2022; Abd-Elsalam, 2024).

Epidemic postharvest diseases represent significant economic losses, often initiated by opportunistic fungal and bacterial pathogens that exploit wounds from harvesting and handling, or reactivate from quiescent infections established in the field. Common postharvest fungal diseases include blue mold (*Penicillium* spp.) and grey mold (*Botrytis cinerea*) on fruits, particularly pome and stone fruits, causing soft, watery rots (De Senna and Lathrop, 2017; Habib *et al.*, 2021; Risoli *et al.*, 2022; Ngah *et al.*, 2024; Dudaš *et al.*, 2025). Anthracnose (*Colletotrichum* spp.) causes sunken lesions and can be quiescent until ripening (Li *et al.*, 2024). Bacterial soft rots, primarily caused by *Erwinia* and *Pectobacterium* species, are major issues for many vegetables, leading to rapid tissue decay (Egorshina *et al.*, 2025). Environmental factors like temperature and humidity, along with fruit maturity and mechanical injury, heavily influence the incidence and severity of these postharvest epidemics (Table 1) (Loc *et al.*, 2022; Danso *et al.*, 2025).

Seed-borne diseases involve pathogens carried on, in, or with the seed, affecting germination, seedling vigor, and potentially leading to significant crop losses. These pathogens, including fungi (e.g., *Fusarium* spp., *Alternaria* spp., *Botrytis* spp.), bacteria (*Xanthomonas* spp., *Pseudomonas* spp.), and viruses (e.g., Alfalfa mosaic virus, Bean yellow mosaic virus), can cause symptoms ranging from pre-emergence damping-off to visible leaf spots, blights, or systemic infections appearing at later growth stages (Risoli *et al.*, 2022; Xu *et al.*, 2022; Ngah *et al.*, 2024; Yu *et al.*, 2024; Martinez *et al.*, 2025; Solórzano *et al.*, 2025). Examples include bunt and loose smut in cereals, caused by *Tilletia* and *Ustilago* respectively, and various *Alternaria* spp. and *Colletotrichum* spp. causing leaf spots and anthracnose. The presence of the pathogen on the seed does not always guarantee disease, as environmental conditions and the location of the inoculum (surface vs. internal) play crucial roles in disease transmission and development (Table 1) (Waqas *et al.*, 2023; Li *et al.*, 2024; Yurchenko *et al.*, 2024).

Host susceptibility is another critical factor in the development of plant diseases (*Ngah et al.,* 2024). Plants possess innate immune systems that can recognize and respond to pathogen attacks, but the effectiveness of these defenses varies widely among species and even among cultivars of the same species (Guo *et al.,* 2024). Genetic factors play a significant role in determining a plant's resistance or susceptibility to specific pathogens (Albanova *et al.,* 2024). For instance, the introduction of resistance genes, such as the R genes in wheat against stem rust, has been a cornerstone of plant breeding efforts to combat diseases (Engelhardt *et al.,* 2018; Xu *et al.,* 2021; Danso *et al.,* 2025). However, pathogens can evolve rapidly, often overcoming host resistance through genetic mutations or recombination. This ongoing "arms race" between plants and pathogens underscores the importance of continuous research and breeding programs to develop new resistant varieties **(Figure 1 and 2)** (Gallois *et al.,* 2018; Cui *et al.,* 2020; Pavese *et al.,* 2021; Danso *et al.,* 2025).

Environmental conditions are perhaps the most dynamic and influential factor in the development of plant diseases (Scalschi *et al.,* 2022). Temperature, soil conditions, rainfall, and humidity can all affect the growth and spread of pathogens, as well as the susceptibility of host plants (Ijaz *et al.,* 2024). For example, many fungal diseases, such as powdery mildew and downy mildew, thrive in warm, humid environments, which promote spore germination and dispersal. Conversely, drought stress can weaken plants, making them more vulnerable to infections by opportunistic pathogens. Climate change is exacerbating these environmental influences, altering the distribution and severity of plant diseases worldwide (Figures 1 and 2) (Valori *et al.,* 2023; Velasquez-Camacho *et al.,* 2023; Mirzwa-Mróz *et al.,* 2024; Rivera-Romero *et al.,* 2024; Aoki and Suzuki, 2025). Rising temperatures and changing precipitation patterns are enabling pathogens to expand their geographic range, while extreme weather events, such as floods and storms, can facilitate the spread of diseases through water and wind (Figs. 1 and 2) (Mareri *et al.,* 2022; Angelotti *et al.,* 2024; Wang *et al.,* 2025).

Human activities also play a significant role in influencing plant diseases (Ma *et al.,* 2022). Agricultural practices such as monoculture, intensive farming, and the overuse of chemical inputs can create conditions that favor the proliferation of pathogens. Monoculture, in particular, reduces genetic diversity and increases the risk of widespread disease outbreaks, as seen in the case of the *Panama* disease epidemic in banana plantations (Buja *et al.,* 2021). Global trade and travel have further accelerated the spread of plant diseases, introducing pathogens to new regions where they can cause significant damage due to the lack of natural resistance or effective management strategies. For example, the introduction of *Phytophthora ramorum*, the causative agent of sudden oak death, to North America and Europe has had devastating effects on native tree populations (Figure 2) (Akhtar *et al.,* 2024; Patejuk *et al.,* 2024; Liu *et al.,* 2025).

The interplay of these factors—pathogen biology, host susceptibility, environmental conditions, and human activities—creates a complex and dynamic system that drives the emergence and spread of plant diseases (Mannaa and Seo, 2021; Ijaz *et al.,* 2024). Understanding these interactions is crucial for developing effective disease management strategies (Angelotti *et al.,* 2024). For instance, integrated pest management (IPM) approaches that combine cultural practices, biological control, and targeted chemical applications can help mitigate the impact of plant diseases while minimizing environmental harm (Angelotti *et al.,* 2024; Giesen *et al.,* 2024). Similarly, advances in genomics and biotechnology offer new opportunities for developing disease-resistant crops and improving early detection and monitoring systems (Figure 2) (Albanova *et al.,* 2023; Guo *et al.,* 2023; Madhushan *et al.,* 2025).

The causes and factors influencing plant diseases are multifaceted and interconnected, requiring a holistic approach to disease management. By addressing the biological, environmental, and human dimensions of plant diseases, researchers, farmers, and policymakers can work together to reduce the impact of these diseases on agriculture, ecosystems, and society (Pavese *et al.,* 2021; Akhtar *et al.,* 2024; Liu *et al.,* 2025). This understanding is not only essential for safeguarding global food security but also for promoting sustainable agricultural practices that balance productivity with environmental stewardship **(Fig. 2)** (Buja *et al.,* 2021).

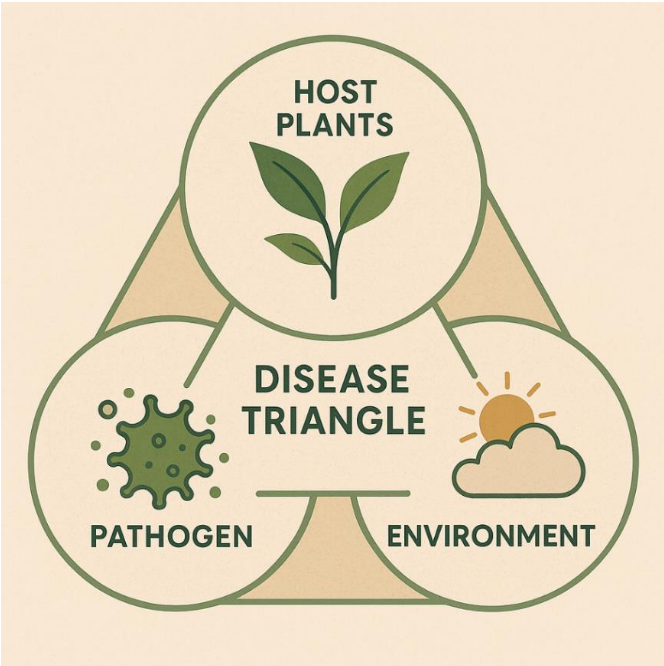

Fig. (1): Disease triangle: Interaction between host, pathogen, and environment.

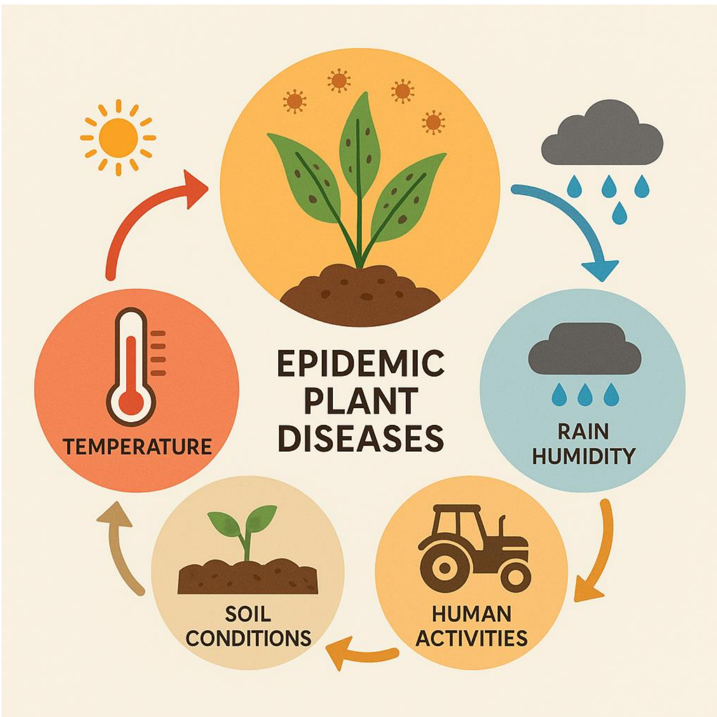

Fig. (2): Key environmental drivers of epidemic plant diseases.

Table (1): Major epidemic plant diseases, their pathogens, diagnostic symptoms, and management applications.

Plant disease (common name)	Scientific Name	Symptoms	Effective Management Methods & Agents
Wheat blast	*Magnaporthe oryzae Triticum*	Bleached, shriveled spikelets; lesions on leaves, nodes, and glumes; often leads to premature plant death.	**Cultural:** Burning infected crop residues, "wheat holidays" (banning cultivation for a period), crop rotation. **Chemical:** Fungicide sprays (e.g., strobilurins, triazoles) as protectants. **Regulatory:** Strict quarantine measures to prevent seed-borne spread.
Banana Fusarium wilt	*Fusarium oxysporum* f. sp. *cubense*	Yellowing and wilting of leaves, starting from older leaves; splitting of pseudostems; internal vascular discoloration; plant death.	**Genetic:** Development and use of resistant/tolerant cultivars (ongoing). **Cultural:** Strict biosecurity measures (preventing movement of contaminated soil, plants, and equipment), exclusion, soil solarization, clean planting material. No effective chemical control for established infections.
Maize lethal necrosis	Maize chlorotic mottle virus	Stunting, severe mosaic or mottling on leaves, leaf reddening, premature drying of leaves, malformed ears, and significant yield loss.	**Genetic:** Use of resistant/tolerant maize varieties. **Cultural:** Vector control (e.g., for thrips, beetles), timely planting, rogueing infected plants, crop rotation, use of clean seed. **Regulatory:** Seed certification programs.
Coffee leaf rust	*Hemileia vastatrix*	Orange-yellow powdery lesions on the underside of leaves; premature defoliation; reduced berry set and vigor.	**Genetic:** Cultivation of resistant coffee varieties. **Chemical:** Fungicidal sprays (e.g., triazoles, strobilurins) applied preventatively or early in infection. **Cultural:** Pruning for improved air circulation, balanced fertilization, shade management.
Tomato brown rugose fruit virus	Tobamovirus (Tomato brown rugose fruit virus)	Mosaic patterns on leaves, rough or wrinkled fruit, brown necrotic spots on fruit, calyx necrosis, reduced yield and quality.	**Cultural:** Strict sanitation (tools, hands, clothing), rapid removal and destruction of infected plants, using certified virus-free seeds/transplants. **Genetic:** Breeding for resistance (emerging). **Regulatory:** Quarantine measures and strict import controls.
Potato late blight	*Phytophthora infestans*	Irregular, water-soaked lesions on leaves that turn brown/black; white fungal growth on undersides of leaves; potato tuber rot.	**Genetic:** Use of resistant potato varieties. **Chemical:** Fungicide sprays (e.g., protectants like chlorothalonil, systemic fungicides like propamocarb, dimethomorph), often in a scheduled program. **Cultural:** Crop rotation, proper plant spacing, hilling, destruction of cull piles, avoidance of overhead irrigation.
Ash dieback	*Hymenoscyphus fraxineus*	Lesions on stems and branches, often leading to necrosis; wilting of leaves; dieback of shoots; crown thinning; eventual tree death.	**Genetic:** Identification and breeding from naturally resistant ash trees. **Cultural:** Sanitation (removing infected trees), replanting with alternative tree species or resistant ash. **Biological:** Research into antagonistic fungi.

4. Economic and Ecological Impacts of Plant Diseases

Plant diseases have far-reaching consequences that extend beyond the immediate damage to crops, affecting economies, ecosystems, and societies on a global scale (Gai and Wang, 2024). Economically, plant diseases are a major threat to agricultural productivity, causing significant yield losses and financial hardships for farmers (Liu *et al.*, 2023). Annual global crop losses due to plant diseases are estimated to range between 20% and 40%, translating to billions of dollars in economic damage (Baylie and Fogarassy, 2021; Cardone *et al.*, 2022). Staple crops such as wheat, rice, maize, and potatoes, which feed billions of people worldwide, are particularly vulnerable to diseases like rusts, blights, and viral infections (Luvisi *et al.*, 2016). For example, wheat stem rust, caused by the fungus *Puccinia graminis*, has the potential to devastate entire harvests, leading to food shortages and price spikes that disproportionately affect low-income populations (Abdedayem *et al.*, 2023; Rehman *et al.*, 2024). Similarly, the spread of Fusarium wilt, caused by *Fusarium oxysporum*, threatens the global banana industry, which is worth billions of dollars and provides livelihoods for millions of smallholder farmers (Solórzano *et al.*, 2025). These economic losses are not limited to crop production but also extend to downstream industries such as food processing, trade, and retail, creating a ripple effect that affects entire economies (Liu *et al.*, 2023; Gai and Wang, 2024).

The ecological impacts of plant diseases are equally profound, often disrupting ecosystems and reducing biodiversity (Scortichini, 2022; Góngora and Silva, 2024). Plants are foundational to terrestrial ecosystems, providing habitat, food, and ecosystem services such as carbon sequestration, soil stabilization, and water regulation. When plant diseases decimate specific species or plant communities, the consequences can cascade through ecosystems, affecting other organisms and ecological processes (Ahmed *et al.*, 2023; Chen *et al.*, 2023; Islam *et al.*, 2024; Picot and Chen, 2025). A striking example is the near-extinction of the American chestnut (*Castanea dentata*) due to chestnut blight, caused by *Cryphonectria parasitica*. Once a dominant tree species in eastern North American forests, the American chestnut played a critical role in supporting wildlife and maintaining ecosystem structure. Its decline has led to significant changes in forest composition and function, with long-term ecological consequences (Dalgleish *et al.*, 2016; Lawson *et al.*, 2021; Ježić *et al.*, 2024). Similarly, the spread of sudden oak death disease, caused by *Phytophthora ramorum*, has devastated oak and tanoak populations in California and Oregon, altering forest dynamics and increasing the risk of wildfires due to the accumulation of dead trees (Haller and Wimberly, 2020; Jung *et al.*, 2021; Kozanitas *et al.*, 2022).

In addition to their direct ecological impacts, plant diseases can also exacerbate environmental degradation through the measures used to control those (Qin *et al.*, 2023). The widespread use of chemical pesticides and fungicides, while effective in managing diseases, often has unintended consequences for non-target organisms, soil health, and water quality (Tsalidis, 2022; Gikas *et al.*, 2022; Rancāne *et al.*, 2023). For instance, the overuse of copper-based fungicides to control diseases like downy mildew and late blight has led to the accumulation of heavy metals in soils, posing risks to beneficial microorganisms, earthworms, and other soil fauna (Massi *et al.*, 2021; Tsalidis, 2022; Dou *et al.*, 2023; Rancāne *et al.*, 2023; Gai and Wang, 2024). Similarly, the runoff of agrochemicals into water bodies can harm aquatic ecosystems, affecting fish, amphibians, and other aquatic organisms. These ecological trade-offs highlight the need for sustainable disease management practices that minimize environmental harm while effectively controlling pathogens (Gikas *et al.*, 2022; Pang *et al.*, 2023; Bai *et al.*, 2024; Wan *et al.*, 2024).

The social consequences of plant diseases are also significant, particularly in developing countries where agriculture is a primary source of income and food security (Cardone *et al.*, 2022). Crop failures caused by diseases can lead to food shortages, malnutrition, and famine, as seen in the Irish Potato Famine of the 1840s, which resulted in the deaths of over one million people and the emigration of millions more (Engler and Werner, 2015). In modern times, plant diseases continue to threaten food security in vulnerable regions, exacerbating poverty and inequality (Gai and Wang, 2024). For example, the spread of wheat stem rust in East Africa has caused severe yield losses, leaving millions of people at risk of hunger and malnutrition (Bhardwaj *et al.*, 2019; Madahana *et al.*, 2021; Rehman *et al.*, 2024). Similarly, the impact of coffee leaf rust in Central America has devastated coffee production, a key source of income for smallholder farmers, leading to economic instability and migration (de Resende *et al.*, 2021; Aristizábal, 2024; Ocaña-Zuñiga *et al.*, 2025). These social consequences underscore the interconnectedness of plant health, food security, and human well-being, highlighting the need for comprehensive and inclusive approaches to disease management (Gai and Wang, 2024).

The economic and ecological impacts of plant diseases are vast and multifaceted, affecting not only agricultural productivity but also environmental health and social stability (Baylie and Fogarassy, 2021; Jung *et al.*, 2021). The economic losses caused by plant diseases threaten global food security and livelihoods, while their ecological consequences disrupt ecosystems and reduce biodiversity (Liu *et al.*, 2023). The social impacts of plant diseases, particularly in developing countries, exacerbate poverty, inequality, and food insecurity (Engler and Werner, 2015; Cardone *et al.*, 2022). Addressing these challenges requires a holistic approach that integrates scientific research, sustainable practices, and policy interventions. By understanding the far-reaching impacts of plant diseases and developing innovative solutions to manage them, we can build more resilient agricultural systems, protect ecosystems, and ensure food security for future generations (Angelotti *et al.*, 2024; Giesen *et al.*, 2024).

5. Management Strategies For Plant Diseases

The plant diseases management is a multifaceted challenge that requires a combination of approaches tailored to the specific pathogen, host, and environmental conditions (Scortichini, 2022). Effective disease management not only aims to reduce the immediate impact of diseases but also seeks to prevent their recurrence and minimize harm to the environment (Akhtar *et al.*, 2024). One of the most fundamental strategies is the use of cultural practices, which involve modifying agricultural techniques to create conditions that are less favorable for pathogens (González-Domínguez *et al.*, 2020). Crop rotation, for instance, disrupts the life cycles of soil-borne pathogens by alternating crops that are non-hosts for specific diseases. This practice is particularly effective against soil borne pathogens like *Fusarium* spp. and *Verticillium* spp., which can persist in the soil for several years (Góngora and Silva, 2024). Similarly, sanitation measures, such as removing and destroying infected plant debris, can significantly reduce the inoculum load and prevent the spread of diseases (Scortichini, 2022). The use of disease-resistant plant varieties, developed through traditional breeding or genetic engineering, is another cornerstone of cultural disease management (Park *et al.*, 2022). Resistant varieties can provide long-term protection against specific pathogens, as seen in the case of wheat varieties resistant to stem rust and rice varieties resistant to bacterial blight (Chopperla *et al.*, 2020).

Biological control represents a sustainable and environmentally friendly approach to managing plant diseases (He *et al.*, 2021). This strategy involves the use of beneficial microorganisms, such as bacteria, fungi, and viruses, to suppress pathogen populations or enhance plant immunity (Borriss and Keswani, 2023). For example, *Bacillus* spp., *Pseudomonas* spp., and the fungus *Trichoderma* spp. are widely used as biocontrol agents against a wide of fungal pathogens (Hasan *et al.*, 2020; Montes-Osuna *et al.*, 2021; Risoli *et al.*, 2022). These beneficial microbes compete with pathogens for nutrition, produce antimicrobial compounds, or induce systemic resistance in plants, thereby reducing disease severity (Andrade-Hoyos *et al.*, 2020). Another promising area of biological control is the use of bacteriophages, which are viruses that infect and kill bacterial pathogens (Gómez-Lama Cabanás & Mercado-Blanco, 2025). Bio-control agents have shown potential in controlling diseases like bacterial spot in tomatoes and fire blight in apples (Gusberti *et al.*, 2015; Akila *et al.*, 2024). While biological control offers numerous advantages, including reduced chemical use and minimal environmental impact, its effectiveness can be influenced by factors such as environmental conditions, host specificity, and the persistence of biocontrol agents in the field (Ayaz *et al.*, 2023; Hartmann and Proença, 2023).

Chemical control remains one of the most widely used strategies for managing plant diseases, particularly in intensive agricultural systems (Cruz-Luna *et al.,* 2023). Fungicides, bactericides, and nematicides are commonly applied to protect crops from infections and reduce yield losses (Ambrose *et al.,* 2023; Bugingo *et al.,* 2025). For instance, systemic fungicides are effective against a broad spectrum of fungal diseases (Takahara *et al.,* 2024). However, the overreliance on chemical control has led to several challenges, including the development of pathogen resistance, environmental contamination, and negative impacts on non-target organisms. The emergence of fungicide-resistant strains highlights the need for judicious use of chemical treatments and the integration of alternative management strategies (Islam *et al.,* 2024). To address these challenges, researchers and farmers are increasingly adopting IPM approaches, which combine chemical control with cultural, biological, and genetic strategies to achieve sustainable disease management (Ons *et al.,* 2020; Gordani *et al.,* 2023; Li *et al.,* 2024).

Genetic engineering and advanced breeding techniques have revolutionized the development of disease-resistant crops, offering new tools to combat plant diseases (Hartmann and Proença, 2023). Techniques such as CRISPR-Cas9 enable precise editing of plant genomes, allowing scientists to introduce or enhance resistance genes without the need for extensive crossbreeding (Erdoğan *et al.,* 2023). Similarly, marker-assisted breeding accelerates the identification and incorporation of resistance genes into elite crop varieties, reducing the time and cost associated with traditional breeding programs (Kumar *et al.,* 2023). While these technologies hold great regulatory hurdles, public perception, and ethical concerns often hinder promise, their adoption (Possamai *et al.,* 2024). Nevertheless, genetic approaches represent a powerful tool for enhancing crop resilience and reducing the reliance on chemical inputs (Song *et al.,* 2023).

Emerging technologies, such as remote sensing, artificial intelligence (AI), and nanotechnology, are also transforming the field of plant disease management. Remote sensing technologies, including drones and satellite imagery, enable the early detection and monitoring of diseases over large areas, allowing for timely interventions (Zhang *et al.,* 2024). AI-powered algorithms can analyze vast amounts of data to predict disease outbreaks and recommend management strategies, improving decision-making and resource allocation (González-Rodríguez *et al.,* 2024). Nanotechnology offers innovative solutions for targeted delivery of agrochemicals, reducing the amount of active ingredients required and minimizing environmental impact (Ray *et al.,* 2023). For example, nano-encapsulated fungicides and bactericides can improve the efficacy and longevity of chemical treatments while reducing off-target effects (Worrall *et al.,* 2018). These technologies, when integrated with traditional management practices, have the potential to revolutionize plant disease management and enhance agricultural sustainability (Han *et al.,* 2022; Prasad *et al.,* 2022; Christakakis *et al.,* 2024; Javidan *et al.,* 2025).

The management of plant diseases requires a holistic and integrated approach that combines cultural, biological, chemical, and genetic strategies (Gusberti *et al.,* 2015; Ons *et al.,* 2020). By leveraging the strengths of each approach and incorporating emerging technologies, farmers and researchers can develop sustainable solutions to mitigate the impact of plant diseases (Christakakis *et al.,* 2024; González-Rodríguez *et al.,* 2024). Effective disease management not only protects crop yields and ensures food security but also promotes environmental health and resilience in the face of evolving challenges (Possamai *et al.,* 2024). As the global population continues to grow and climate change exacerbates the threat of plant diseases, the development and adoption of innovative management strategies will be critical for building a sustainable and resilient agricultural system (Ayaz *et al.,* 2023).

6. Emerging Technologies and Future Directions in Plant Disease Management

The field of plant disease management is undergoing a transformative phase, driven by advances in technology and a growing emphasis on sustainability. Emerging technologies, such as remote sensing, AI, nanotechnology, and microbiome engineering, are revolutionizing the way plant diseases are detected, monitored, and controlled (Ray *et al.,* 2023; Christakakis *et al.,* 2024; Javidan *et al.,* 2025). These innovations offer new opportunities to enhance the precision, efficiency, and sustainability of disease management practices, while also addressing the challenges posed by climate change, pathogen evolution, and the need for food security (Prasad *et al.,* 2022). Remote sensing technologies, including drones, satellites, and ground-based sensors, are enabling the early detection and real-time monitoring of plant diseases over large areas. By capturing high-resolution images and multispectral data, these tools can identify subtle changes in plant health, such as variations in chlorophyll content or canopy temperature, which may indicate the presence of disease. Besides drones equipped with hyperspectral cameras have been used to detect late blight in potato fields and citrus greening in orchards, allowing farmers to take targeted action before the disease spreads (Han *et al.,* 2022; Prasad *et al.,* 2022; Zhang *et al.,* 2024). When combined with AI algorithms, remote sensing data can be analyzed to predict disease outbreaks, assess risk levels, and recommend management strategies, thereby improving decision-making and resource allocation (Javidan *et al.,* 2025).

Artificial intelligence and machine learning are playing an increasingly important role in plant disease management, offering powerful tools for data analysis, pattern recognition, and predictive modeling (González-Rodríguez *et al.*, 2024). AI-powered systems can process vast amounts of data from diverse sources, including weather records, soil samples, and plant health indicators, to identify trends and correlations that may not be apparent to human observers (Prasad *et al.,* 2022; Kohut *et al.,* 2025). For instance, AI models have been developed to predict the spread of wheat rust and coffee leaf rust based on environmental conditions and historical disease data (Routis *et al.,* 2024). These predictive capabilities enable farmers to implement preventive measures, such as adjusting irrigation schedules or applying fungicides, before disease outbreaks occur (Rodríguez-Lira *et al.,* 2024). Additionally, AI-driven image recognition apps allow farmers to diagnose diseases in the field using smartphone cameras, providing instant recommendations for management (Khan *et al.,* 2025). By democratizing access to advanced diagnostic tools, these technologies empower smallholder farmers to make informed decisions and reduce crop losses (Yağ and Altan, 2022; Javidan *et al.*, 2025).

Nanotechnology is another promising frontier in plant disease management, offering innovative solutions for the targeted delivery of agrochemicals and the development of novel antimicrobial agents (Kutawa *et al.,* 2021). Nano-encapsulation techniques can improve the efficacy and longevity of fungicides and bactericides by controlling their release and protecting them from degradation (Abd-Elsalam, 2024). This not only reduces the amount of active ingredients required but also minimizes environmental contamination and off-target effects. Nanoparticles made from materials such as silver, copper, and zinc oxide have shown antimicrobial properties against a wide range of plant pathogens, including fungi, bacteria, and viruses (Worrall *et al.,* 2018). For instance, silver nanoparticles have been used to control Fusarium wilt in tomatoes, while zinc oxide nanoparticles have demonstrated efficacy against *Xanthomonas* infections in rice (Macías Sánchez *et al.,* 2023; Wang *et al.,* 2023). Despite their potential, the use of nanotechnology in agriculture raises concerns about safety, regulatory approval, and public acceptance, highlighting the need for rigorous research and transparent communication (Worrall *et al.,* 2018; Khan *et al.,* 2021).

Microbiome engineering is an emerging field that seeks to harness the potential of plant-associated microbes to suppress diseases and enhance plant health (Ali *et al.,* 2023; Misu *et al.,* 2025). The plant microbiome, which includes bacteria, fungi, and other microorganisms living on and within plants, plays a critical role in nutrient acquisition, stress tolerance, and disease resistance (Noman *et al.,* 2021; Joshi *et al.,* 2025). By manipulating the composition and function of the microbiome, researchers can develop microbial consortia that protect plants from pathogens or enhance their immune responses (Meshram and Adhikari, 2024). Similarly, the use of mycorrhizal fungi can improve plant resilience to soil-borne pathogens by enhancing root health and nutrient uptake (Ferreira *et al.,* 2024; Hadian *et al.,* 2025). Advances in metagenomics and synthetic biology are accelerating the discovery and engineering of beneficial microbes, paving the way for next-generation biocontrol products (Glick and Gamalero, 2021; Tariq *et al.,* 2025).

Climate-resilient crops are another critical area of focus for future plant disease management. As climate change alters temperature and precipitation patterns, it is expected to exacerbate the spread and severity of plant diseases, particularly in regions where crops are already grown at the limits of their climatic tolerance (Kopeć, 2024). Breeding and engineering crops with enhanced resistance to both biotic and abiotic stresses will be essential for ensuring food security in a changing climate. For example, heat-tolerant and drought-resistant varieties of wheat, rice, and maize are being developed to withstand the combined pressures of climate change and disease (Bouri *et al.*, 2023; Sugumar *et al.*, 2024). Genetic engineering techniques, such as CRISPR-Cas9, offer precise tools for introducing or enhancing resistance genes, while marker-assisted breeding accelerates the development of resilient crop varieties (Erdoğan *et al.,* 2023).

Global collaboration and knowledge sharing will be essential for addressing the complex and interconnected challenges of plant disease management. International initiatives, such as the Global Rust Reference Center and the International Plant Protection Convention, play a vital role in monitoring disease outbreaks, sharing data, and coordinating responses (Shahin *et al.*, 2022; Rodríguez-Vázquez *et al.*, 2023). By fostering partnerships between researchers, policymakers, and farmers, these initiatives can facilitate the development and adoption of innovative solutions. Additionally, public awareness and education campaigns can help bridge the gap between scientific advancements and on-the-ground implementation, ensuring that farmers have access to the tools and knowledge they need to protect their crops (Abo-Elyousr *et al.*, 2022; Prahl *et al.*, 2022).

The future of plant disease management lies in the integration of emerging technologies, sustainable practices, and global collaboration (Worrall *et al.*, 2018; Javidan *et al.*, 2025). By leveraging the power of remote sensing, AI, nanotechnology, microbiome engineering, and genetic innovation, we can develop more effective and environmentally friendly strategies to combat plant diseases (Yağ and Altan, 2022; Kohut *et al.*, 2025). These advancements will not only safeguard global food security but also promote the resilience and sustainability of agricultural systems in the face of evolving challenges. As we move forward, it is imperative to prioritize research, investment, and policy support to ensure that these technologies are accessible and beneficial to all, particularly smallholder farmers in developing countries (González-Rodríguez *et al.,* 2024; Joshi *et al.*, 2025; Kohut *et al.*, 2025).

Conclusion

Plant diseases stand as a major, multifaceted challenge to global agriculture, directly threatening food security, economic stability, and environmental health. As this review has demonstrated, the sheer diversity of pathogens—from persistent fungi and destructive bacteria to pervasive viruses and damaging nematodes—underscores the complexity of the issue. These diseases are not isolated events but rather the product of a dynamic interplay among susceptible hosts, fluctuating environmental conditions, and human agricultural practices. The profound economic losses, ecological disruptions, and social inequalities caused by plant diseases, vividly illustrated by historical crises like the Irish Potato Famine, highlight the urgent and ongoing need for integrated and sustainable disease management strategies.

Conflict of interest

The authors declare that they do not have any actual or potential conflict of interest.

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