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A Comprehensive Review on Plant Disease Vectors and Their Management

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Authors' contributions

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

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ABSTRACT

Plant disease vectors play a critical role in agricultural productivity and ecosystem health. This comprehensive review explores the intricate nature of these vectors and their role in transmitting major plant diseases, including those of viral, bacterial, and fungal origins. It delves into the mechanisms underlying disease transmission, and the significant factors that influence vector efficiency. The socioeconomic and ecological impacts of these vectors are highlighted, with emphasis on crop yield reductions and ecological imbalances. Traditional and emerging vector management methods, such as chemical control, biological control, cultural practices, genetic

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engineering, and precision agriculture are examined. The review also addresses the challenges inherent to vector management, including resistance development, non-target effects, environmental factors, and socioeconomic barriers. Future perspectives are offered, emphasizing the need for sustainable strategies, exploitation of emerging technologies, enhanced surveillance, community involvement, policy support, and preparation for forthcoming challenges due to climate change, land-use alterations, and global trade. This extensive review presents a critical resource for stakeholders in plant disease vector management, guiding future research directions and policy-making.

Keywords: Impacts; management; plant-disease; transmission; vector.

1. INTRODUCTION

The world of agriculture faces myriad challenges, ranging from a changing climate, burgeoning human populations, to a diversity of pests and diseases [1]. Among the formidable adversaries that plants encounter, disease vectors occupy a unique and significant position. Plant disease vectors are organisms that transmit pathogens from an infected host to a healthy one, thereby causing a myriad of plant diseases [2]. This review aims to explore the comprehensive landscape of plant disease vectors and elaborate on the effective strategies for their management. The profound impact of plant disease vectors on agriculture, food security, and ecosystem health is undeniable. Pests and diseases destroy approximately 20-40% of global crop production annually [3]. Vectors such as insects, nematodes, and mites contribute to this loss by transmitting harmful pathogens [4]. Consequently, the ability to understand and manage these vectors is vital for ensuring global food security, conserving biodiversity, and maintaining the health of our ecosystems [5].Traditionally, vector control strategies have relied on chemical pesticides. However, the harmful environmental impacts and emerging pesticide resistance issues associated with these chemicals underscore the necessity for alternative, sustainable management practices [6]. Over the past few decades, scientific research has increasingly focused on these alternatives, investigating biological control agents, plant breeding for disease resistance, and integrated pest management strategies [7]. The field of plant disease vectors has benefited from recent technological advancements, leading to a more nuanced understanding of vector-pathogen interactions and enhanced disease management strategies. Modern genetic techniques, precision agriculture technologies, and computational tools have empowered researchers to decipher complex vector-pathogen-plant interactions, forecast disease outbreaks, and devise targeted control strategies. Despite these advancements, challenges persist. Overcoming these hurdles requires a multidisciplinary approach, harnessing insights from entomology, plant pathology, molecular biology, ecology, and social sciences [8]. This review intends to contribute to this multidisciplinary understanding by providing a comprehensive exploration of plant disease vectors and their management. We start by outlining the basics of plant disease vectors, their roles in transmitting major plant diseases, and the impacts they have on crop productivity and the economy. The review then explores current and innovative management strategies, evaluates their effectiveness, and highlights potential challenges and future directions. It seeks to offer a reference guide for researchers, policymakers, farmers, and other stakeholders involved in plant disease vector management.

2. PLANT DISEASE VECTORS

Plant disease vectors are a diverse group of organisms that transmit pathogens from one plant to another, thereby spreading diseases [9]. These vectors, comprising insects, mites, nematodes, and other animals, play a pivotal role in plant health and agricultural productivity. The classification of plant disease vectors primarily stems from their taxonomy and the modes of disease transmission they facilitate [10]. Insects, particularly those belonging to Hemiptera such as aphids, whiteflies, leafhoppers, and plant hoppers, are the most common vectors of plant diseases [11]. Other arthropods, such as mites, can also transmit viruses [12]. Among non-arthropod vectors, nematodes are crucial, especially in the transmission of viruses [13].The life cycles of these vectors and their biological activities considerably influence the transmission of plant diseases [14]. Insects such as aphids have multiple generations per year, allowing for rapid population growth and consequent disease spread [15]. Furthermore, many vectors exhibit plant host preference, which directly impacts the pattern and intensity of disease spread [16]. The interaction between vectors and plant pathogens is intricate and has been a subject of extensive investigation. Vector-pathogen interactions can be broadly classified into two categories: non-persistent or stylet-borne and persistent or circulative transmission [17]. In non-persistent transmission, the pathogen does not multiply within the vector, and the transmission happens quickly. Contrarily, in persistent transmission, pathogens not only multiply within the vector but may also be passed across generations, resulting in more prolonged and efficient transmission [18]. The behavior of vectors influences the transmission dynamics. For example, the probing behavior of aphids directly affects the transmission of viruses. Aphids sample plant cells using their stylets, and during this probing activity, viruses can attach to the stylets and be subsequently transmitted to other plants [19]. Moreover, pathogens can manipulate the vectors' feeding behavior to enhance their own transmission. The cucumber mosaic virus (CMV) alters the host plant's volatiles, making it more attractive to aphids, which in turn aids in the spread of the virus [20]. While much progress has been made in understanding vector-pathogen-plant interactions, much remains to be discovered. The advent of modern molecular techniques and genomics has allowed researchers to uncover the complex interactions at a molecular level. For example, transcriptomic studies have identified vector genes that are responsive to pathogen infection, which could be potential targets for disrupting disease transmission [21]. Understanding the biology and behavior of vectors is paramount in developing effective disease management strategies. However, the complexity of vector-pathogen-plant interactions and the continual evolution of vectors and pathogens make this a challenging endeavor. Nonetheless, continued research and advancements in technology are gradually shedding light on these complex interactions, offering hope for more sustainable and effective disease management strategies in the future.

3. MAJOR PLANT DISEASES TRANSMITTED BY VECTORS

Vector-borne diseases are a significant challenge for the global agricultural industry, leading to considerable crop yield losses (Table 1) [22]. One of the most notorious diseases transmitted by vectors is the Citrus Greening Disease (or Huang Long Bing, HLB), primarily spread by the Asian citrus psyllid (*Diaphorina citri*). HLB, caused by the bacterium *Candidatus liberibacter* spp., can lead to severe yield losses and even the death of citrus trees [23]. The symptoms include yellowing of leaves, premature fruit drop, and off-tasting fruits, rendering the produce unfit for consumption [2 4].Another major disease transmitted by insect vectors is the Maize streak virus (MSV), which is spread by the leafhopper *Cicadulina mbila*. MSV, belonging to the Geminiviridae family, is a significant threat to maize production, particularly in Sub-Saharan Africa. Infected plants show chlorotic streaks on leaves, stunted growth, and can lead to total crop loss under severe infection [25]. Mosaic diseases, caused by several types of viruses, are other important diseases spread by vectors. For example, the Cucumber mosaic virus (CMV), spread by aphids, affects a wide range of plants including cucumbers, tomatoes, and peppers, leading to mosaic patterns on leaves, stunted growth, and reduced yield [26]. Similarly, the Tobacco mosaic virus (TMV), although not primarily vector-borne, can be spread by insects and causes similar symptoms in tobacco and other Solanaceae family members [27]. Nematodes, too, are significant vectors of plant diseases. One of the most damaging is the Potato cyst nematode (*Globodera rostochiensis* and *G. pallida*), which transmits the potato 'spraing' disease caused by Tobacco rattle virus (TRV). Infected plants exhibit necrotic rings in tubers, reducing both yield and quality [28]. Some fungal diseases can also be vectored by insects, such as the Dutch elm disease (DED). DED, caused by the fungi *Ophiostoma ulmi* and O. novo-ulmi, is transmitted by elm bark beetles. This disease has led to substantial losses of elm trees across North America and Europe, with symptoms including wilting, branch dieback, and eventual tree death [29]. Plant diseases transmitted by vectors not only affect agricultural productivity but also have significant socio-economic impacts. The mitigation of these diseases often requires intensive pest management strategies, which can lead to increased costs for farmers and potential environmental damage. Furthermore, these diseases can threaten food security in many regions, particularly where smallholder farming dominates [30]. Given the immense burden of vector-borne plant diseases on agriculture and food security, it is crucial to invest in research

Table 1. Major plant diseases transmitted by vectors

Disease Name	Vector	Pathogen	Primary Host Plants	Reference
Citrus Greening Disease (Huang Long Bing)	Asian citrus psyllid (*Diaphorina citri*)	*Candidatus liberibacter* spp.	Citrus species	[32]
Maize Streak Virus (MSV)	Leafhopper (*Cicadulina mbila*)	Maize streak virus	Maize	[33]
Cucumber Mosaic Disease	Aphids	Cucumber mosaic virus (CMV)	Cucumbers, tomatoes, peppers	[34]
Tobacco Mosaic Disease	Various insects	Tobacco mosaic virus (TMV)	Tobacco and other Solanaceae family plants	[35]
Potato 'spraing' disease	Potato cyst nematodes (*Globodera rostochiensis* and *G. pallida*)	Tobacco rattle virus (TRV)	Potato	[36]
Dutch Elm Disease	Elm bark beetles	Fungi (*Ophiostomaulmi* and *O. novo-ulmi*)	Elm trees	[37]

and development of efficient, environmentally friendly, and sustainable vector and disease management strategies. These may include integrated pest management, biological control, plant breeding for resistance, and precise forecasting models for disease prediction and prevention [31].

4. ROLE OF VECTORS IN DISEASE TRANSMISSION

Understanding the role of vectors in disease transmission is pivotal to devising effective strategies for managing plant diseases. Vectors act as intermediaries, picking up pathogens from infected plants and subsequently transmitting them to healthy ones, thus playing a crucial role in the spread and establishment of various plant diseases [38]. Insects are among the most significant vectors for plant diseases, particularly viruses, bacteria, and phytoplasmas. The process of disease transmission via insects involves intricate interactions between the insect vector, the pathogen, and the plant host. When an insect feeds on an infected plant, the pathogen enters the insect's body, after which it can be transmitted to a healthy plant when the insect feeds again [39]. Aphids are notorious vectors for several plant viruses. These insects use their piercing-sucking mouthparts to feed on plant phloem, where they inadvertently pick up viruses and transmit them to other plants. Notable among these viruses are the Potato virus Y (PVY) and the Cucumber Mosaic Virus (CMV) [40]. Leafhoppers and planthoppers are vectors for many viral, bacterial, and phytoplasmal diseases. The Rice Tungro Bacilliform Virus (RTBV) and the Maize Streak Virus (MSV) are examples of viral diseases transmitted by leafhoppers [41]. In some cases, vectors not only transmit the pathogen but also contribute to the disease's pathology. An example is the Asian citrus psyllid, which transmits the bacterium *Candidatus liberibacter* asiaticus, causing the *Huang Long Bing* (HLB) disease. This psyllid's feeding activity induces phloem collapse, contributing to the overall symptomatology of HLB [42]. Nematodes, microscopic worms, are also significant vectors, particularly for viral diseases. For example, the Tobacco rattle virus (TRV), causing the corky ringspot disease in potatoes, is transmitted by the stubby root nematode (*Paratrichodorus allius*) [43]. Fungi and fungal-like organisms such as oomycetes can also act as vectors for certain plant viruses, such as the Soil-Borne Wheat Mosaic Virus (SBWMV), transmitted by the fungus *Polymyxa graminis*. Disease transmission by vectors is not a random event; it is influenced by several factors, including vector behavior,

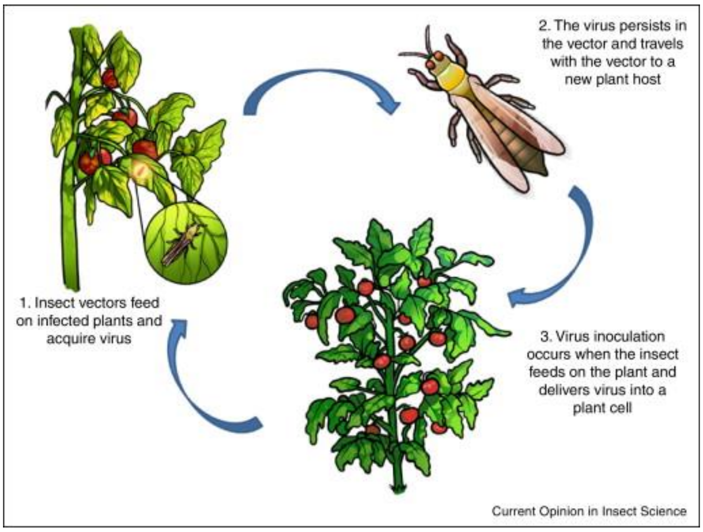

Plate 1. Disease transmission by vector
Source: (Whitfield & Rotenberg) [47]

population dynamics, pathogen virulence, and environmental conditions. Understanding these factors can aid in devising targeted and effective disease management strategies [44]. Vectors' role is not limited to disease transmission (Plate 1). They can also shape the evolution of pathogens, influencing their virulence and transmission efficiency. Co evolutionary dynamics between vectors, pathogens, and hosts are significant areas of research that can shed light on disease emergence, spread, and management [45]. The role of vectors in disease transmission underscores the need for integrated pest management strategies to control both the vectors and the pathogens they carry. Such strategies may include biological control, habitat manipulation, use of disease-resistant varieties, and application of insecticides and fungicides. However, the sustainability and environmental impact of these strategies should be considered (Heimpel & Mills, 2017) [46].

5. IMPACTS OF PLANT DISEASE VECTORS

The impacts of plant disease vectors are multifaceted and far-reaching, affecting a broad range of aspects from agricultural productivity to environmental sustainability and global food security [48]. The impact is not limited to the direct effects on crop yield and quality but also extends to socio-economic consequences and biodiversity loss.

- **Agricultural Productivity:** The most immediate and tangible impact of plant disease vectors is on agricultural productivity. Vectors transmit a multitude of plant diseases that can reduce crop yield and quality. For example, the Asian citrus psyllid (*Diaphorina citri*), the vector of the devastating Huanglongbing (HLB) disease, has resulted in substantial losses in citrus production globally [49].
- **Economic Consequences:** The economic impacts of plant disease vectors can be staggering, given their effects on crop losses and the costs of managing these diseases. The economic burden extends from the individual farmer level to national and global scales. For example, the direct and indirect costs of the whitefly-transmitted Tomato yellow leaf curl virus (TYLCV) are estimated in the billions of dollars annually [50].
- **Food Security:** The detrimental effects of plant disease vectors on crop production directly threaten global food security. Given that the world's population is projected to reach 9.7 billion by 2050, the challenge of producing enough food is further exacerbated by vector-borne diseases (FAO, 2019) [51].
- **Environmental Impact:** Vectors can lead to significant environmental impacts, primarily through the measures taken to control them. Heavy reliance on chemical pesticides to control vectors can lead to environmental contamination, loss of biodiversity, and the development of pesticide resistance [52].

- **Biodiversity Loss:** Vector-borne diseases can lead to a loss of biodiversity, particularly when vectors and pathogens are introduced to new areas where hosts have not evolved resistance. This is the case with the elm bark beetle, which has decimated elm populations across North America and Europe by spreading the Dutch elm disease [53].
- **Socio-Economic Consequences:** Beyond the farm, plant disease vectors can have broader socio-economic consequences, affecting livelihoods, and contributing to poverty and inequality. The impacts are particularly pronounced in developing countries where agriculture is a significant part of the economy and a primary source of livelihood [54].
- **Climate Change Interactions:** Climate change can influence the distribution and abundance of vectors, thus impacting disease incidence and distribution. Rising temperatures can expand the geographic range of vectors and increase their reproductive rates, leading to more significant disease problems [55].

6. CURRENT APPROACHES TO VECTOR MANAGEMENT

Effective vector management is a cornerstone of sustainable plant disease management. It involves a multi-faceted approach that targets both the vector and the disease it transmits. The strategies employed are primarily informed by the nature of the vector, the host plant, and the disease-causing agent.

- **Cultural Practices:** These involve modifications of agricultural practices to create an environment less conducive to vectors. Practices include crop rotation, which disrupts the life cycle of the vector; intercropping, which reduces vector mobility by providing a physical barrier; and timing of planting and harvesting to avoid peak vector activity periods [56].
- **Host Plant Resistance:** Breeding disease-resistant or vector-resistant crop varieties is a long-term strategy for vector management. By introducing resistance genes into susceptible crop varieties, the plant's ability to resist vector attack or pathogen infection is enhanced. This method has been successful in managing several vector-transmitted diseases, such as barley yellow dwarf virus transmitted by aphids and Maize streak virus transmitted by leafhoppers [57].
- **Biological Control:** This method involves the use of natural enemies of the vector to suppress their populations. Parasitoids, predators, and pathogens can be employed to control vector populations. *Encarsia formosa*, a parasitoid wasp, is used against the whitefly vector of Tomato yellow leaf curl virus [58].
- **Chemical Control:** Insecticides and Acaricides can be applied to control vector populations. However, their indiscriminate use can lead to resistance development, harm non-target organisms, and cause environmental pollution. Hence, they are ideally used as part of an integrated pest management strategy [59].
- **Genetic Control:** This method involves altering the vector's genetic makeup to reduce their ability to transmit diseases. Techniques include the release of insects carrying dominant lethal genes (RIDL), sterile insect technique (SIT), and the use of gene drives. However, these methods are mainly applied to manage disease vectors in human and animal health [60].
- **Behavioral Manipulation:** This involves exploiting the vector's behaviors to manage their populations. Techniques include the use of trap crops, pheromone traps, and push-pull strategies. Colored sticky traps are used to manage whiteflies and thrips, vectors of several plant viruses [61].

The current approaches to vector management are not foolproof, and their success largely depends on factors such as the vector's biology, environmental conditions, and socio-economic factors. There is a need for continued research to improve these strategies and explore new methods for vector management. Future developments may include the use of precision agriculture techniques, next-generation breeding techniques, and novel biological and chemical control agents. Adopting a systems approach, integrating multiple strategies, and involving stakeholders in vector management decisions can enhance the effectiveness and sustainability of vector management efforts [62].

7. INNOVATIVE TECHNOLOGIES FOR VECTOR MANAGEMENT

Innovative technologies are playing an increasingly important role in improving vector management strategies, enabling more efficient, environmentally friendly, and sustainable pest control.

7.1 Precision Agriculture Technologies

Precision agriculture involves the use of advanced technologies to optimize agricultural productivity and sustainability. GPS, remote sensing, GIS (Geographical Information Systems), and machine learning algorithms can be used to monitor vector populations, detect diseases early, and target interventions more accurately. These technologies enable the efficient use of resources, minimize environmental impact, and improve crop yields [63].

- **RNA Interference (RNAi):** RNAi is a biological process where RNA molecules inhibit gene expression, effectively silencing targeted genes. In vector management, RNAi can be utilized to suppress essential genes in vectors, disrupting their life cycle and disease transmission ability. Studies have shown the potential of RNAi in controlling aphids, whiteflies, and other vectors [64].
- **CRISPR-Cas9:** The revolutionary CRISPR-Cas9 gene-editing technology offers significant potential for vector management. By altering the genetic makeup of vectors, their ability to transmit diseases can be reduced. Gene drives can also be engineered to spread desirable traits rapidly through vector populations, though ethical and ecological considerations need careful attention [65].
- **Biopesticides:** Biopesticides are derived from natural materials, such as animals, plants, bacteria, and certain minerals. These environmentally friendly alternatives to chemical pesticides are effective against vectors while being less harmful to non-target species and the environment. The development of novel biopesticides is a promising field for sustainable vector management [66].
- **Nanotechnology:** Nanotechnology in agriculture has shown promise in several areas, including pest management. Nano-pesticides can improve the efficiency of active ingredients, reduce non-target effects, and prevent the development of resistance. Additionally, nanosensors can enhance disease and vector detection capabilities [67].
- **Genomic Technologies:** Genomic technologies, including next-generation sequencing, provide detailed insights into the genetic makeup of vectors and pathogens. This knowledge can inform the development of targeted control measures, enhance surveillance capabilities, and facilitate the early detection of resistance development [68].

7.2 Challenges in Vector Management

Despite the advancement in vector management strategies, several challenges persist that hamper the effective control of plant disease vectors. A deeper understanding of these challenges can help in developing more effective and sustainable strategies.

- **Vector Diversity and Complexity:** The diversity and complexity of vectors contribute to the challenges faced in their management. The behavioral, physiological, and genetic variations among different vector species necessitate the development of tailor-made control strategies. Their adaptive responses to changing environmental conditions and control interventions further complicate this process [69].
- **Insecticide Resistance:** Repeated and indiscriminate use of chemical insecticides can lead to the development of resistance among vectors, making these chemicals ineffective over time. The development and spread of resistance among vector populations is a significant global concern and poses a severe challenge to effective vector management [70].
- **Non-Target Impacts:** Both chemical and biological control strategies can have unintended effects on non-target species, potentially harming beneficial organisms and disrupting ecological balance. These consequences pose ethical dilemmas and add to the challenges of managing vectors [71].
- **Environmental Factors:** Environmental factors such as climate change and habitat alteration can influence vector populations and their distribution patterns. These factors can alter the vectors' breeding patterns, host preferences, and disease transmission potential, which can complicate control efforts [72].
- **Socio-Economic Factors:** Socio-economic factors such as poverty,

inadequate infrastructure, lack of knowledge, and limited access to control technologies can also pose significant challenges to vector management. Overcoming these barriers requires effective policy-making, increased funding, and community engagement [73].

- **Regulatory and Ethical Issues:** The use of innovative technologies such as genetic control and gene editing raises regulatory and ethical issues. Concerns about their potential ecological impacts, long-term effects, and ethical implications necessitate careful consideration and stringent regulatory mechanisms [74].
- **Emerging and Re-Emerging Diseases:** The emergence and re-emergence of vector-borne diseases due to changes in land use, climate change, and global travel and trade further complicate vector management. Continuous monitoring and surveillance, rapid response capabilities, and regular updates of control strategies are necessary to address this challenge [75].

Despite these challenges, the ongoing advancements in science and technology offer hope for more effective and sustainable vector management in the future. Integrated and multidisciplinary approaches, incorporating innovative technologies and considering ecological, socio-economic, and ethical aspects, are critical to overcoming these challenges [76].

8. FUTURE PERSPECTIVES AND RECOMMENDATIONS

The battle against plant disease vectors will require continuous advancements and adaptations in our strategies. The emerging technologies and methodologies provide hope for the future. However, their successful implementation will need comprehensive efforts from researchers, farmers, policy-makers, and other stakeholders. Here are some perspectives and recommendations for future actions.

- **Emphasize Sustainable Approaches:** The focus should shift towards more sustainable and environmentally friendly vector management approaches, minimizing reliance on chemical pesticides. This includes enhancing the use of biological control agents, adopting integrated pest management (IPM) strategies, and promoting the use of bio-pesticides [77].
- **Utilize Emerging Technologies:** Emerging technologies such as CRISPR, RNAi, and precision agriculture offer significant potential for vector management. However, their application will require further research, training of personnel, and development of appropriate regulatory frameworks [78].
- **Invest in Research and Development:** There should be increased investment in research and development activities focused on understanding vector biology, ecology, and epidemiology. This would aid in the development of targeted control strategies, the early detection of resistance, and the forecasting of disease outbreaks [79].
- **Promote Collaborative and Integrated Approaches:** The successful control of plant disease vectors necessitates collaborative and integrated approaches involving entomologists, plant pathologists, geneticists, ecologists, and other stakeholders. Integrating different knowledge domains will foster the development of holistic vector management strategies [80].
- **Enhance Surveillance and Monitoring:** Robust surveillance and monitoring systems should be established for early detection and timely intervention. Advanced technologies such as remote sensing and geographical information systems can play a significant role in this regard [81].
- **Foster Capacity Building and Community Engagement:** Capacity building efforts should be enhanced, including training farmers in pest management techniques, educating communities about vector-borne diseases, and promoting citizen science initiatives. Community engagement is crucial for the successful implementation of vector control strategies [82].
- **Advocate for Supportive Policies and Regulations:** Supportive policies and regulations are needed to facilitate the adoption of innovative technologies, promote sustainable farming practices, and encourage the commercialization of biopesticides. Policy interventions can also help address socio-economic barriers to effective vector management [83].

- **Prepare for Future Challenges:** With changing climatic conditions, expanding agricultural landscapes, and global trade, future challenges in vector management will undoubtedly emerge. Preparing for these challenges requires adaptive strategies, continuous updates of knowledge, and a flexible approach to pest management [84].

9. CONCLUSION

The management of plant disease vectors is critical for global food security and ecosystem health. An in-depth understanding of these vectors, the diseases they transmit, and their socio-ecological impacts is necessary for effective control. Current control strategies range from traditional methods to cutting-edge technologies, each with its strengths and limitations. Looking ahead, the focus should be on developing sustainable, integrated, and adaptive strategies that leverage emerging technologies while considering environmental and socio-economic factors. Collaborative research, enhanced surveillance, capacity building, and supportive policies will be pivotal in this endeavor. The future of plant disease vector management lies in our ability to innovatively respond to the evolving threats posed by these vectors, ensuring agricultural sustainability and global food security.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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