Integrated approaches for management of Whitefly (*Bemisia tabaci* Gennadius) to Prevent Chilli Leaf Curl Disease in Chilli Crop: A Review

Abstract

Whitefly (*Bemisia tabaci* Gennadius) poses significant agricultural challenges due to its role as a vector for plant viral diseases, particularly the Chilli leaf curl disease (ChiLCD). This review discusses the multifaceted management strategies and elaborates on the future prospects and research directions to combat these threats. Precision agriculture is identified as a pivotal tool, with the utilization of drones, machine learning, and automated pesticide application offering early pest detection and targeted interventions. Exploration of novel biological controls, including RNA interference and microbiome manipulation, provide innovative avenues for sustainable pest management. A notable concern remains the development of resistance in pests. Genomic studies and an in-depth understanding of biochemical pathways have shed light on potential strategies to address resistance build-up mechanisms. Behavioral studies elucidate the adaptive changes in pests in response to pesticides. Effective management is not solely reliant on technological and biological advancements. Strengthening the linkages between farmers, extension services, and researchers is essential for the dissemination and practical application of research findings. Digital platforms, participatory research, and feedback mechanisms have emerged as beneficial in this context. While significant challenges persist in the management of *Bemisia tabaci* and ChiLCD, integrated approaches that combine advanced technology, innovative research, and robust stakeholder partnerships offer a promising pathway forward. This synthesis underscores the importance of interdisciplinary collaborations and continuous research in shaping sustainable agricultural practices.

Keywords: Chilli Leaf Curl Disease, Precision-agriculture, Resistance, Vector Whitefly

Introduction

Whiteflies, particularly the species *Bemisia tabaci* Gennadius, have long been identified as significant pests in the world of agriculture. Originating from the family *Aleyrodidae*, Order, *Hemiptera*, this particular whitefly has managed to wreak havoc across various agricultural landscapes, with its omnipresence felt from leafy greens to fruit-bearing trees [1]. The gravity of its impact is especially felt in the cultivation of chilli crops, where these seemingly innocuous insects play a nefarious role in the spread of the chilli leaf curl disease (ChiLCD). The life cycle of *B. tabaci* is fascinatingly complex, a trait that aids its adaptability and resilience. Following a pattern that's reminiscent of most insects, it starts as an egg, predominantly found on the underside of leaves, providing a modicum of protection. Upon hatching, the larvae, or nymphs, begin their journey, navigating across the leaf surface, feeding on sap, and gradually evolving.

After a series of molts, these nymphs transform into a pupal stage, eventually emerging as adults, ready to continue the lineage. This life cycle, while intriguing the whitefly has an ability to rapidly populate within a plant, especially under favorable conditions [2]. What truly magnifies the significance of *B. tabaci* in the agricultural arena is not merely its feeding habits or reproductive capabilities, but its role as a vector for a multitude of plant pathogens. The direct damage due to its feeding, are chlorosis and wilting, is compounded by the indirect harm via the transmission of viral diseases [3]. Its impact, that economic assessments frequently pinpoint substantial financial losses attributable to whitefly infestations. Crops in tropical and subtropical zones, owing to their climatic advantages, often suffer the most, with the economic burden running into billions [4]. Among the various ailments spread by the whitefly, ChiLCD has emerged as a predominant concern for chilli cultivators. The causative agent behind ChiLCD is a ssDNA virus that finds its taxonomy under the genus Begomovirus. While the disease itself manifests in symptoms like stunted growth, leaf curling, and a marked reduction in fruit size and quality, its transmission mechanism is of paramount importance. Whiteflies, during their sap-sucking endeavors, ingest the virus from infected plants. This virus then establishes itself within the whitefly, only to be subsequently introduced to a new host during the next feeding session, thus perpetuating a vicious cycle of infection and re-infection [5]. The implications for chilli crop production can't be understated. In regions, that pride themselves on chilli cultivation, such as India, yield losses can oscillate between a concerning 20% to a devastating 100%, contingent on factors like infestation intensity and the chilli variety in question [6]. Given these overwhelming challenges, the call for an integrated approach to manage these threats becomes not just necessary but imperative. This is where integrated pest management (IPM) enters the discourse. Rooted in principles of sustainability and environmental conservation, IPM is articulated as a methodology that amalgamates various tools be they biological, cultural, chemical, or physical in an orchestrated manner to minimize risks associated with pests, both to the environment and the economy [7]. The philosophical underpinning of IPM stems from a profound understanding of ecosystems and a nuanced perspective on pest behavior. The intent isn't the eradication but the management of pest populations, ensuring they remain below levels that would cause economic harm [8]. Historically, the predominant strategy to combat agricultural pests was chemical intervention. Pesticides, with their promise of rapid results, became the mainstay of pest control efforts. Over time, a slew of challenges associated with their unabated use began surfacing. From the emergence of pesticide-resistant pest strains to the environmental repercussions of chemical runoffs, the pitfalls became too glaring to ignore. The concerns about food safety, underscored by pesticide residues on consumables, added another layer of complexity to the narrative [9]. Hence, the need for a more holistic, informed, and balanced approach epitomized by IPM became palpable.

Biology and Ecology of *Bemisia tabaci*

Understanding the biology and ecology of any pest is paramount for its effective management. The whitefly, *B. tabaci,* is no exception. This tiny insect, appearing almost inconspicuous to the naked eye, poses significant agricultural threats across a myriad of crops. A detailed exploration into its life cycle, host range, migratory behaviors, and the environmental factors affecting its populations provides insights pivotal for its integrated management. The life cycle of *B. tabaci* is an intricate journey comprising various stages: eggs, nymphs (four instars), and adults (Figure 1). Beginning as an egg, often deposited on the underside of leaves, the whitefly's life cycle is initiated [10]. These eggs, pale in coloration initially, darken over time and hatch within 5-7 days, depending on environmental conditions. Upon hatching, the first nymphal instar, commonly referred to as a "crawler", migrates short distances to locate an ideal feeding spot. The subsequent instars second, third, and fourth are sessile and look like scale insects. They feed by inserting their stylets into plant phloem, and as they develop, they molt, shedding their exoskeleton, a process witnessed three times before they transition into the pupal stage. This stage is a precursor to their adulthood. The transformation from egg to adult generally spans 2-3 weeks but can vary based on ambient conditions such as temperature and humidity [11]. One of the quintessential attributes that accentuate the menace of *B. tabaci* is its extensive host range. Researchers have identified more than 600 plant species as potential hosts [12]. This host repertoire spans multiple families including but not limited to Solanaceae, Fabaceae, and Cucurbitaceae. Crops like tomatoes, beans, cotton, and cucurbits frequently find themselves under siege from whitefly infestations. While *B. tabaci* has a broad host range, its preference can exhibit variation based on biotypes. Some biotypes exhibit a proclivity for specific hosts, underlining the role of genetic factors in determining host specificity [13]. Whiteflies, much like other agricultural pests, exhibit migratory behaviors that are pivotal for their survival and propagation. Adult whiteflies are winged and hence capable of flight, allowing them to migrate and infest new areas. While individual flight distances might be limited, typically in the range of a few kilometers, wind currents can significantly augment these distances, facilitating their spread across vast regions [14]. Migratory patterns of *B. tabaci* are not random. They are influenced by factors such as host availability, environmental conditions, and intraspecific competition. Seasonal shifts, especially in regions with pronounced variations in climate, can also stimulate migratory events as the whiteflies move in search of more favorable habitats [15]. Environmental factors profoundly influence the population dynamics of *B. tabaci*. Among these, temperature and humidity stand out as paramount. The optimal temperature for whitefly development hovers around 27 °C. Deviations from this, especially extreme temperatures, can negatively impact their survival and reproductive rates. Temperatures beyond 35°C can be lethal for eggs and nymphs, while adult whiteflies demonstrate reduced longevity and fecundity under such conditions [16].

Relative humidity also plays a significant role. High humidity levels are conducive for whitefly development, with optimal ranges being between 60-80%. Conversely, low humidity conditions can desiccate eggs and nymphs, resulting in higher mortality [17]. Light intensity can influence whitefly behavior. Higher light intensities stimulate increased feeding and reproduction rates, while suboptimal light conditions can retard their development and reduce population densities [18].

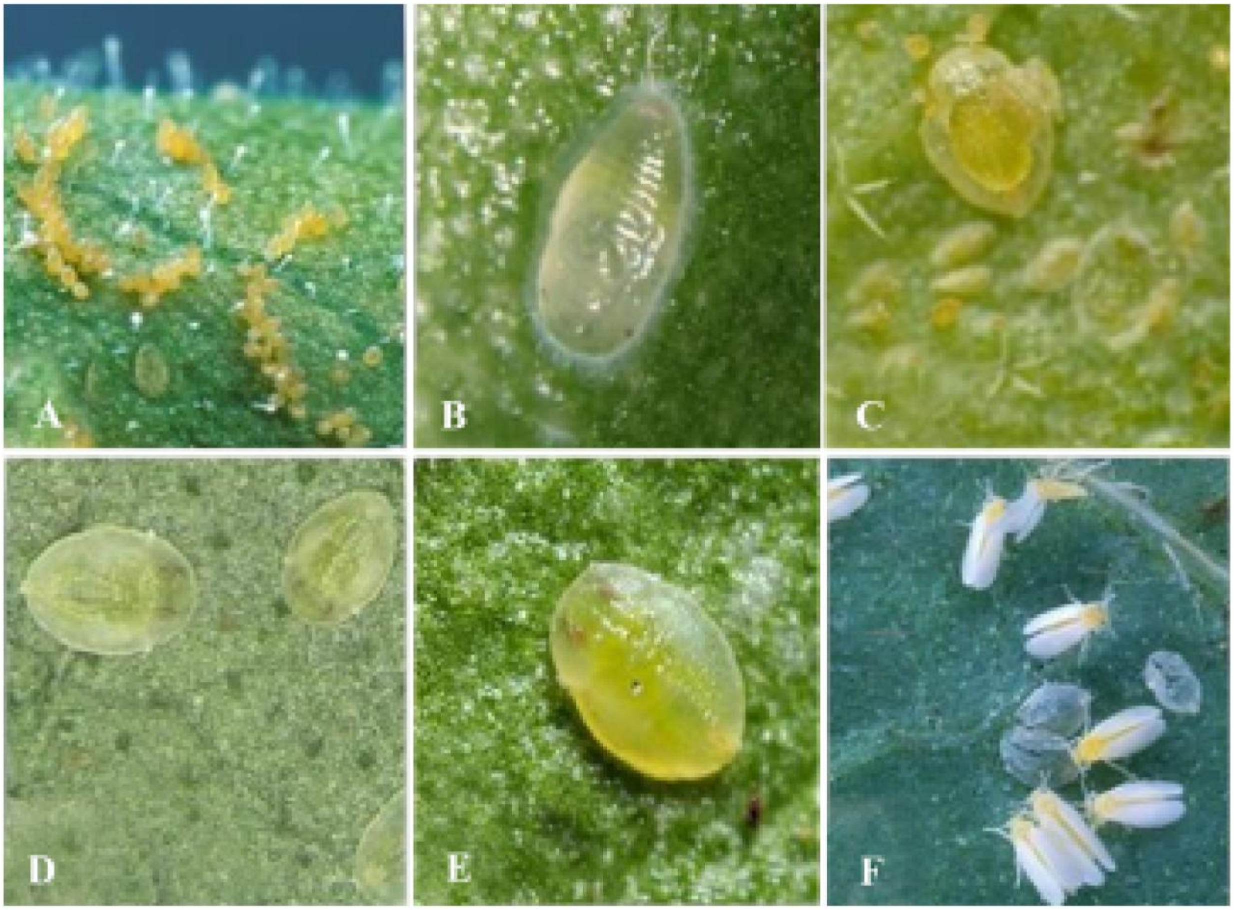

Figure 1: The whitefly life cycle. (A) Oval-shaped eggs attached to the leaf via a stalk-like structure for fluid uptake, (B) the 1st instar nymph, (C) 2nd, 3rd, and 4th instar nymphs, (D) red-eyed 4th instar nymph, (E) pharate adult stage or pupal stage, (F) emergence of adult whiteflies after metamorphosis leaving the transparent shells. (Source:https://www.mdpi.com/)

Mechanism of Disease Transmission by *Bemisia tabaci*

Bemisia tabaci, is a prominent vector responsible for transmitting plant viruses, particularly the Chilli leaf curl virus (Chil LCV). Understanding the mechanism by which *B. tabaci* transmits diseases aids in devising strategies to curtail the spread of these pathogens, thus protecting our crops and ensuring food security.

A. Direct Feeding Damage

B. tabaci causes direct harm to plants through its feeding activities. Adult and nymph stages of the whitefly feed on plant sap by piercing the phloem with their needle-like mouthparts and withdrawing nutrients [19]. Such direct feeding leads to several detrimental effects: Loss of vigor: As the whiteflies withdraw nutrients, plants lose vital sap which leads to a reduction in their vigor and growth rate. In severe infestations, the plant's growth can be stunted, and yield reduced [20]. Honeydew production: While feeding, whiteflies excrete a sugary substance known as honeydew. This secretion serves as a substrate for sooty mold growth, reducing the photosynthetic efficiency of the plant. The mold blackens the leaf surface, inhibiting light absorption, and thereby curbing photosynthesis [21]. Leaf shedding and curling: Infestations often lead to premature leaf shedding and curling. Such leaves display chlorosis due to disrupted chlorophyll synthesis, primarily due to nutrient depletion by the whiteflies feeding [22].

B. Vector-mediated Transmission of Chilli leaf curl virus

The menace of *B. tabaci* is not restricted to the damage caused by direct feeding. This whitefly serves as a vector for several plant viruses, with the chilli leaf curl virus (ChiLCV) being one of the most notorious [23]. The mechanism of transmission can be elucidated as follows: Acquisition: When a whitefly feeds on an infected plant, it acquires the virus. The virus binds to specific receptors in the insect's gut, a process that typically takes a few minutes to hours [24]. Circulation and Retention: Post-acquisition, the virus moves through the insect's alimentary canal, eventually reaching the salivary glands. The virus can be retained within the whitefly for several days to weeks [25]. Inoculation: Upon feeding on a healthy plant, the whitefly releases the virus into the plant's phloem, thereby transmitting the disease. The infected plant starts showing symptoms like leaf curling, stunted growth, and reduced yield, characteristic of ChiLCV [26].

C. Virus-Whitefly Interactions

The relationship between the virus and *B. tabaci* is not merely a passive one. There exists an intricate interplay between the two: Facilitated reproduction: Some studies suggest that plants infected with viruses such as ChiLCV become more susceptible to whitefly infestations. The virus alters the plant's physiology, making it a more attractive host for the whiteflies, potentially facilitating the insect's reproduction [27]. Enhanced viral acquisition: Viruses can modify the feeding behavior of *B. tabaci*. Infected plants produce specific volatiles that attract more whiteflies, thereby amplifying the chances of viral acquisition and subsequent transmission [28]. Fitness costs: On the flip side, harboring and transmitting the virus may come with fitness costs for *B. tabaci*. Some studies have noted a slight reduction in whitefly longevity and fecundity when they are carriers of specific viruses [29].

Challenges in managing *Bemisia tabaci* and chilli leaf curl disease

The profound impact of *B. tabaci* on global agriculture is underscored by its role in the spread of various plant diseases, most notably CLCuD. While integrated management strategies have been proposed, their successful implementation is hampered by various challenges. Herein, it explores the prominent hurdles encountered in managing both the pest and the disease. One of the foremost strategies to control whitefly populations has been the use of chemical insecticides. These chemicals have been historically seen as an immediate solution due to their rapid mode of action. Reliance on these chemicals has resulted in a series of challenges: Development of resistance: Continual exposure to insecticides has led to the emergence of resistant *B. tabaci* populations. This resistance is often conferred through mutations in target genes or enhanced metabolic detoxification [30]. Over the years, whiteflies have shown resistance to various classes of insecticides, including organophosphates, pyrethroids, and neonicotinoids [31]. Resurgence and secondary pest outbreaks: Often, the use of insecticides not only fails to control the primary pest but also inadvertently suppresses the natural enemies of other pests. This can lead to a sudden increase in secondary pests that were previously under control [32]. Environmental and health concerns: Many insecticides, particularly older generation chemicals, have detrimental impacts on the environment. Their residue can persist in plant produce, soil and water, affecting non-target organisms and posing risks to human health [33]. Climate change, characterized by increasing temperatures, altered precipitation patterns, and increasing atmospheric CO_2 levels, presents another layer of complexity in managing whitefly populations. Extended life cycle: Rising temperatures can potentially shorten the life cycle of *B. tabaci.* A shorter life cycle means quicker reproduction rates, leading to larger populations within a shorter timeframe [34]. Shift in Distribution: Climatic changes may render previously unsuitable habitats more favorable for whiteflies. As temperatures rise, *B. tabaci* might expand its geographical range, infesting new regions that were previously free from this pest [35]. Altered plant-whitefly interactions: Elevated CO_2 levels can change the nutritional quality of host plants. While some studies suggest that increased CO_2 can make plants less nutritious for whiteflies, others indicate that whiteflies may compensate by feeding more, thereby causing more damage [36]. Farmers are the frontline warriors in the battle against pests and diseases. They face their set of challenges: Knowledge gap: Not all farmers are equipped with the knowledge of the latest integrated pest management (IPM) practices. Many still rely on traditional or outdated methods, which might be less effective or even counterproductive [37]. Economic constraints: Sustainable practices such as biocontrol or crop rotation might have initial costs that are higher than traditional chemical control. Many small-scale farmers might find it financially challenging to adopt such measures [38]. Cultural and social barriers: In many regions, farming practices have deep cultural roots. Changing such practices might be met with resistance, not just due to lack of knowledge, but also because of societal norms and traditions [39].

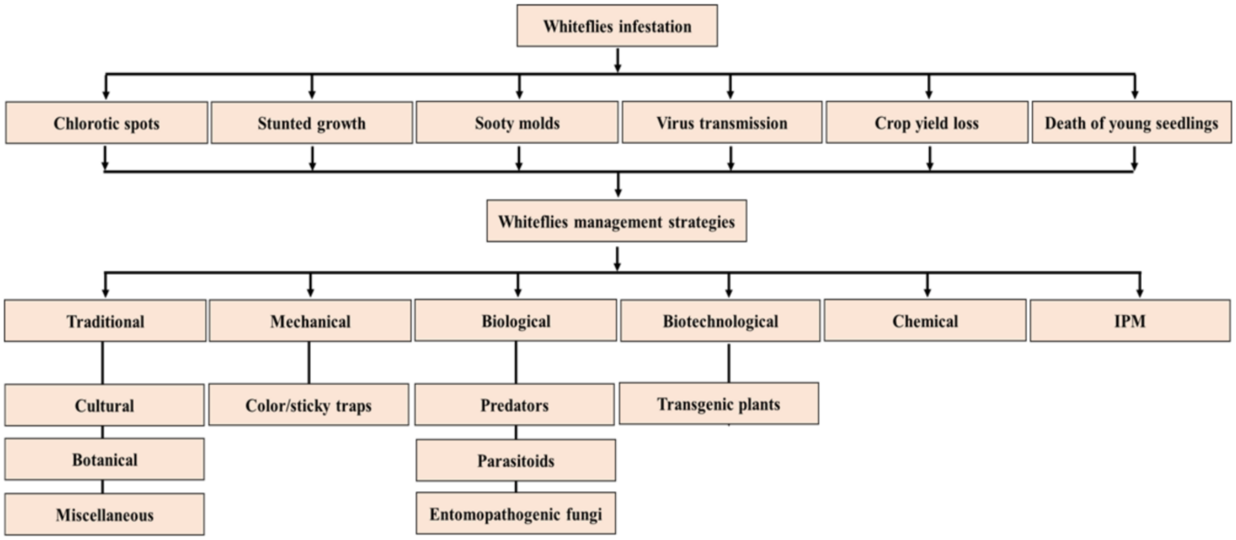

Figure 2: A schematic representation of the available whitefly management (WFM) strategies. (Source: https://www.mdpi.com/)

Components of Integrated Management

Integrated pest management (IPM) represents a comprehensive strategy for sustainable pest and disease control, drawing upon a combination of techniques, informed by the ecological context and socio-economic considerations [40]. With the growing challenges posed by *B. tabaci* and the consequential ChiLCD, there is a pressing need to adopt a holistic approach. Let's delve into the key components of this integrated management.

A. Cultural practices

Cultural practices, essentially agronomic techniques that can help deter pests, are the first line of defense in an IPM program. Crop rotation: The continual planting of chillies can enhance the buildup of whitefly populations. Introducing a different crop (Agathi) disrupts the whitefly lifecycle, thereby reducing its population [41]. Intercropping: Planting chillies alongside non-host plants (Agathi, *Sesbania grandiflora*) can disrupt the whiteflies' searching behavior, making it harder for them to locate their preferred host [42]. Adjusting planting time: Synchronizing planting times with periods of low whitefly populations or unfavorable conditions can minimize initial infestations [43].

B. Biological control

Biological control agents act as natural enemies to pests and can suppress their populations. Predators: Ladybird beetles and lacewings are voracious predators of whiteflies. They can be introduced or conserved in the field to limit whitefly populations [44]. Parasitoids: Parasitoids like *Encarsia formosa* lay their eggs in whitefly nymphs, leading to their death. These parasitoids have been successfully used in greenhouse conditions for whitefly control [45]. Pathogens: Certain fungi, bacteria, and viruses are pathogenic to whiteflies. The fungus *Beauveria bassiana* infects and kills whiteflies, offering a biopesticide alternative [46].

C. Chemical control

Chemical control remains an essential component but needs to be applied judiciously to avoid development of resistance and environmental harm. Botanical insecticides: Derived from plants, these offer a more eco-friendly alternative. Neem-based products, such as neem oil, neem seed kernel extract have shown efficacy against whiteflies [47]. Neonicotinoids and their alternatives: Neonicotinoids, like imidacloprid, are potent against whiteflies, concerns over resistance and environmental implications necessitate alternatives. Sulfoxaflor and flupyradifurone are upcoming replacements [48]. Judicious chemical use: Over-reliance on chemicals can spur resistance. Rotating chemicals, using them in combination with other control methods, and avoiding unnecessary applications can prevent resistance buildup [49].

D. Genetic Control

Advancements in breeding and biotechnology offer avenues for genetic control. Resistant cultivars: Breeding chilli varieties (Teja, Tejaswini and Yashaswini etc.) resistant to whitefly or the virus can reduce reliance on insecticides. Several resistant cultivars have been identified, albeit with varying degrees of success [50]. Genetically Modified Chillies: While controversial, genetic modifications can confer resistance against whiteflies or the virus. Research in this direction, combined with public acceptance, could offer a robust solution [51].

E. Behavioral and Physical Methods

These methods exploit the behavioral traits of whiteflies to manage them. Yellow sticky traps: Whiteflies are attracted towards the yellow color. Sticky traps can be used to monitor and reduce whitefly populations [52]. Reflective ulches: Mulches with aluminium surfaced plastic and straw that reflect sunlight can deter whiteflies from settling on the plants, reducing infestation rates [53].

F. Monitoring and Surveillance

For IPM to succeed, timely decisions based on accurate information are vital. Early Detection: The sooner a pest or disease outbreak is identified, the more effectively it can be managed. Techniques such as or remote sensing can aid early detection by yellow sticky traps [54]. Forecasting: Predictive models using weather data, previous infestation patterns, and other variables can forecast potential whitefly outbreaks, facilitating proactive management [55].

G. Farmer Training and Community Participation

For effective implementation, farmers and the community at large must be knowledgeable and involved. IPM is as much about education as it is about technique. Training programs to educate farmers on whitefly biology, IPM principles, and sustainable practices can significantly enhance outcomes [56].

Future Prospects and Research Directions

The persistence and spread of *B. tabaci* and the associated ChiLCD present an ever-evolving challenge for agricultural scientists, farmers, and policymakers. As the global agricultural landscape becomes more interconnected and as pests and pathogens adapt to changing environments and management practices, innovative approaches are essential. Herein, it will explore future prospects and potential research directions, emphasizing technology, novel biological controls, resistance mechanisms, and enhanced stakeholder linkages. The advent of technology has ushered in a new era of precision agriculture, which, at its core, is about applying the right treatment, at the right place, at the right time [57]. For managing pests like *B. tabaci*, such precision can make a difference. Remote sensing and Drones: Drones equipped with multispectral cameras can detect pest infestations before they are visible to the human eye, allowing for early interventions [58]. Machine Learning and Predictive Analytics: can predict outbreaks based on various factors such as weather patterns, past infestations, and cropping patterns, enabling preemptive measures [59]. Automated Pesticide Application: can ensure that pesticides are applied in the right amounts and only when necessary, reducing costs, environmental impact, and resistance buildup [60]. Beyond the traditional biological controls, new frontiers are being explored, driven by a deeper understanding of ecology and biotechnology. RNA Interference (RNAi): could be employed to disrupt the genes essential for the survival or reproduction of the pest. For *B. tabaci*, RNAi could target genes vital for its growth or its ability to transmit viruses [61]. Microbiome Manipulation: could potentially impair the pest's ability to reproduce or survive [62]. Resistance is an ongoing challenge in pest management. A deeper understanding of the mechanisms behind it can inform more sustainable strategies. Genomic Studies: bsed on the genome of *B. tabaci* can shed light on the genes responsible for resistance, enabling targeted interventions [63]. Biochemical Pathways can help in understanding the biochemical pathways that allow the whitefly to detoxify pesticides, this can develop molecules that bypass or block these pathways. Behavioral Resistance: Sometimes, pests simply avoid the pesticide, by not feeding on treated plants. Observing and understanding these behavioral changes can guide strategy modifications. Knowledge generation is only half the battle. Effective transmission and application of that knowledge are equally crucial. Digital Extension Platforms using: Mobile apps and online platforms can provide farmers with real-time information on pest outbreaks, recommended practices, and even market prices [64]. Participatory Research involving farmers in the research process can ensure that the solutions developed are practical and tailored to the ground realities. Feedback Loops can establishing mechanisms where farmers can provide feedback on recommended practices ensures that the research remains relevant and adapts to the changing conditions.

Conclusion

In addressing the challenges posed by *B. tabaci* and ChiLCD, future strategies must amalgamate advanced technological innovations with fundamental biological understandings. Precision agriculture, exploiting drones and predictive analytics, promises early detection and targeted interventions. Novel biological controls, such as RNA interference and microbiome manipulation, offer potential avenues for sustainable management. A deeper comprehension of resistance mechanisms will be pivotal in designing robust interventions. Importantly, strengthening farmer-extension-research linkages will ensure that innovations are not only relevant but also effectively disseminated. In essence, a multifaceted approach that integrates technology, biology, and robust stakeholder partnerships will be vital for the sustainable management of these agricultural threats.

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